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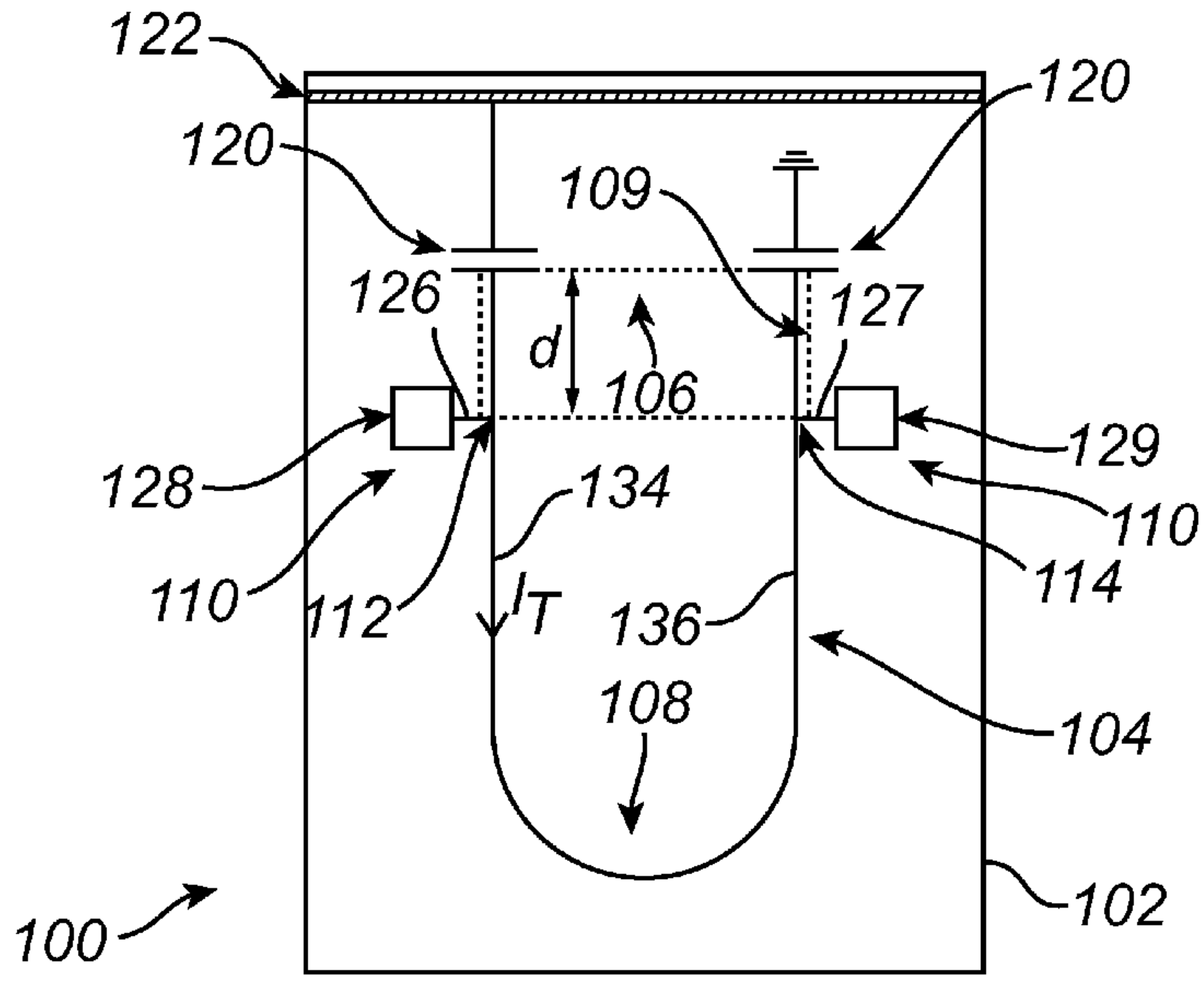

Fig. 1A

(57) Abstract: The present invention relates to a tunable microwave resonator device (100, 200) having an associated base wavelength, the microwave resonator device comprising: a dielectric substrate (102); an electrically conductive line pattern (104) supported by the dielectric substrate, the electrically conductive line pattern having an open end (106) and a closed end (108), a tuning arrangement (110) adapted to provide a tuning electric current (IT) into the electrically conductive line pattern for tuning a resonance frequency of the microwave resonator device, the tuning arrangement is adapted to pass the electric current from a first point (112) of the electrically conductive line pattern to a second point (114) of the electrically conductive line pattern, wherein the first point and the second point are located a predetermined distance (d) from the open end, wherein the predetermined distance is based on a length of a quarter base wavelength.

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TUNABLE MICROWAVE RESONATOR

Field of the Invention

The present invention generally relates to a tunable microwave resonator device.

Background

Microwave resonators are versatile devices that can be used for various applications such as in filter, amplifiers, and in some sensing applications. With the recent advance in quantum computing architectures microwave resonators have also been used as qubit communication buses.

The base frequency of a microwave resonator is defined by the geometry of the resonator. Adjusting the base frequency can therefore be made by varying the geometry of the resonator. However, mechanical solutions for adjusting the base frequency are technically complicated and only provide for relatively slow tuning of the base frequency.

Another approach includes tuning the kinetic inductance of a superconducting microwave resonator by means of applying a magnetic field to the superconducting resonator. This does not require mechanically adjusting the resonator geometry but suffers from slow tuning of the base frequency.

Attempts have been made to integrate so-called superconducting quantum interference devices (SQUIDs) into the resonator design. This allows for controlling the nonlinear inductance of Josephson junctions of the SQUID with an external magnetic field to in this way tune the base frequency of the resonator. However, insertion of the Josephson junctions degrades the resonance quality, often defined by the so-called Q-value.

Accordingly, there appears to be a need for improvements with regards to tunable microwave resonators.

Summary

In view of the above-mentioned and other drawbacks of the prior art, it is an object of the present invention to provide an improved tunable microwave resonator.

According to a first aspect of the present invention, it is therefore provided a tunable microwave resonator device having an associated base wavelength, the microwave resonator device comprising: a dielectric substrate; an electrically conductive line pattern supported by the dielectric substrate, the electrically conductive line pattern having an open end and a closed end, a tuning arrangement adapted to provide a tuning electric current into the electrically conductive line pattern for tuning a resonance frequency of the microwave resonator device, the tuning arrangement is adapted to pass the electric current from a first point of the electrically conductive line pattern to a second point of the electrically conductive line pattern, wherein the first point and the second point are located a predetermined distance from the open end, wherein the predetermined distance is based on a length of a quarter base wavelength.

The present invention is based on the realization that the resonance frequency of the microwave resonator can be tuned by injecting an electric current at appropriate locations in the microwave resonator. The injected tuning electrical current flows in the closed part of the electrically conductive line pattern and effectively tunes the inductance of the closed part of the electrically conductive line pattern. The inventors realized that it is advantageous to inject the tuning electric current approximately a quarter base wavelength from the open end of the electrically conductive line pattern. In this way, the losses from the electrically conductive line pattern through the injection point may be reduced since the injection points are located near voltage nodes of the microwave mode of the resonator.

More specifically, a section of the electrically conductive line pattern from the first and second point to the open end acts an impedance converter for providing a low impedance path at the resonance frequency of the tunable

microwave resonator. In other words, a “microwave short” is provided between the first point and the second point.

Accordingly, the quarter base wavelength part of the electrically conductive line pattern, from the first and second point to the open end, provides an impedance converter. The open end of the impedance converter provides an infinite impedance at the open end, whereas a low impedance path at least at the resonance frequency is provided between the first point and the second point. The “path” is provided by that a voltage node is located at the first point and the second point, while at the same time a high current is provided in the corresponding current pattern of the tunable microwave resonator. In other words, at the location of the first point and the second point, a low voltage and a high current is present at the resonance frequency, thereby providing a low impedance path.

A length of a quarter base wavelength is the length of a quarter, i.e. 25% of the base wavelength.

A base wavelength is defined by the configuration of the microwave resonator device. Thus, the design of electrically conductive line pattern determines the base wavelength, whereby the electrically conductive line pattern is designed to tailor the base wavelength to a given application associated with a predetermined operation frequency.

Generally, the performance of a resonator may be quantified by the so-called quality factor, often denoted Q, i.e. the Q-factor, which is a dimensionless factor. In a microwave resonant circuit, the Q-factor may be provided by the formula

$$Q = \frac{f_0}{f_{3dB}},$$

where f_0 is the center resonance frequency and f_{3dB} is the bandwidth, i.e. frequency span, of the frequency response of the microwave resonant circuit at the -3dB point, i.e. when the response has dropped by 3dB. The quality factor is well known in the field of microwave resonant circuits and will not be described in more detail herein.

In view of the above Q-factor discussion, tuning a resonance frequency of the microwave resonator device relates to shifting or altering f_0, i.e. the center resonance frequency of the microwave resonator device, from a first resonance frequency to a second or further resonance frequency by injecting DC electric current into the electrically conductive line pattern.

The tuning of the resonance frequency may be performed in dependence of a varying tuning electric current. In other words, the resonance frequency may be a function of the tuning electric current. For example, continuously increasing the tuning electric current may continuously reduce the resonance frequency.

The electrically conductive line pattern may take any pattern but should provide for a structure that is associated a base wavelength and thus a resonance frequency.

The tuning electric current may be a direct current, i.e. a tuning DC electric current. Alternatively, the tuning electric current may be an alternating current, i.e. a tuning AC electric current, preferably with a frequency less than the resonance frequency.

The first point may be electrically connected to the second point through the closed end, and further through a capacitive coupling parallel with the closed end.

Preferably, the microwave resonator may comprise a first electrically conductive member and a second electrically conductive member, wherein the first electrically conductive member is electrically connected to the first point for providing the tuning electric current to the first point, and the second electrically conductive member is electrically connected to the second point for draining the tuning electric current from the second point.

The first electrically conductive member and the second electrically conductive member may preferably be capacitively coupled to each other. The capacitive coupling may be adapted to provide a near zero, e.g. negligible, impedance at the resonance frequency of the tunable microwave resonator. This advantageously provides for eliminating any residual voltage at the first and second points on the electrically conductive line pattern that may be present due to finite fabrication tolerances that cause the first and second point to be shifted from zero voltage points on the electrically conductive line pattern. This further means that radiation losses through the first and second points are reduced, or even eliminated.

Accordingly, the capacitive coupling between the first electrically conductive member and the second electrically conductive member may advantageously provide a low impedance path at the resonance frequency of the tunable microwave resonator device.

With the inventive concept, fast tuning of the microwave resonator is obtained while at the same time providing high Q-factors. With herein described tunable microwave resonance devices, Q-factors exceeding 100 000, even as high as 1000 000 have been obtained with a tuning time below 20 ns, and a tuning range of about 2%.

At the closed end of the electrically conductive line pattern the electrically conductive line pattern is continuous such that an electric current may travel therethrough.

The electrically conductive line pattern is not connected at the open end. In order for a DC electric current to travel from one side of the open end to the other side of the open end, the electric current travels via the closed end.

The predetermined distance may be an electrical distance, in other words, the distance that a microwave signal propagates. This is regardless of the shape or outline of the conductive line pattern. If the conductive line pattern from the first point to the open end is a straight line, the predetermined distance is the length of the conductive line from the first point to the open end.

The predetermined distance may be the length of the conductive line of the electrically conductive line pattern from the first point to the open end. Further, the distance from the second point to the open end is also the predetermined distance.

That the predetermined distance is based on a length of a quarter base wavelength should be interpreted broadly. The predetermined distance may deviate from a quarter base wavelength by some amount, such as a few percent of a quarter base wavelength. The predetermined distance may be a distance the microwave signal propagates across the conductive line patter for a quarter of the microwave signal period.

In embodiments, the first point and the second point may be at a respective location associated with a voltage node of the tunable microwave resonator. Accordingly, the first point and the second point may be located where the residual voltage is negligible. This may advantageously provide for further reduced losses and improved quality factor of the microwave resonator.

In embodiments, the tuning electric current may be injected through the first point and drained through the second point.

In embodiments, the electrically conductive pattern may comprise a first line segment including the first point and a second line segment including the second point, wherein the first line segment and the second line segment are connected at the closed end. Although not strictly required, the first line segment and the second line segment may be substantially parallel. For example, the electrically conductive line pattern may be substantially U-shaped.

A line segment is a segment of electrically conductive material that may carry the tuning electric current and that may serve as part of the resonator structure. A line segment is configured to carry microwave signals.

In embodiments, the tunable microwave resonator may comprise electrically conductive lines supported by the substrate for connecting a DC power source to the first point and the second point. The electrically conductive lines, being part of the tuning arrangement, are terminal lines that provide an electrically conductive path for injecting the tuning electric current to the first point and for draining the tuning electric current from the second point.

In embodiments, the tunable microwave resonator device may be adapted to be capacitively or inductively coupled to a read-out transmission line.

In embodiments, the read-out transmission line may be supported by the substrate.

In embodiments, the electrically conductive line pattern may be planar.

In embodiments, the tunable microwave resonator device may be manufactured by thin film technology.

In embodiments, the electrically conductive line pattern may advantageously be made from a superconductor material. This provides for tuning the kinetic inductance of the superconducting electrically conductive line pattern using the tuning electric current.

Superconducting materials are *per se* known to the skilled addressee. Generally, a superconducting material has no electrical resistance when cooled below a material specific transition temperature.

The tunable microwave resonator device may comprise an electric ground plane supported by the dielectric substrate, wherein the tuning DC electric current may be injected into the electrically conductive line pattern via the electric ground plane.

Further features of, and advantages with, the present invention will become apparent when studying the appended claims and the following description. The skilled addressee realizes that different features of the present invention may be combined to create embodiments other than those described in the following, without departing from the scope of the present invention.

Brief Description of the Drawings

These and other aspects of the present invention will now be described in more detail, with reference to the appended drawings showing an example embodiment of the invention, wherein:

Fig. 1A conceptually illustrates a tunable microwave resonator device according to embodiments of the invention;

Fig. 1B schematically illustrates a voltage pattern and a current pattern for a microwave mode of a tunable microwave resonator device according to embodiments of the invention;

Fig. 1C conceptually illustrates a tunable microwave resonator device according to embodiments of the invention;

Fig. 1D schematically illustrates a voltage pattern and a current pattern for a microwave mode of a tunable microwave resonator device according to embodiments of the invention;

Fig. 2 conceptually illustrates a tunable microwave resonator device according to embodiments of the invention;

Fig. 3A schematically illustrates a tunable microwave resonator device according to embodiments of the invention; and

Fig. 3B schematically illustrates a tunable microwave resonator device according to embodiments of the invention.

Detailed Description of Example Embodiments

In the present detailed description, various embodiments of a microwave resonator device according to the present disclosure are described. However, the microwave resonator device may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided for thoroughness and completeness, and to fully convey the scope of the present disclosure to the skilled person. Like reference characters refer to like elements throughout.

Fig. 1A conceptually illustrates a tunable microwave resonator device 100 having an associated base wavelength, λ. The microwave resonator device 100 comprises a dielectric substrate 102 and an electrically conductive line pattern 104 supported by the dielectric substrate 102. The electrically conductive line pattern 104 having an open end 106 and a closed end 108. Further, the microwave resonator device 100 comprises a tuning arrangement 110 adapted to provide a tuning electric current into the electrically conductive line pattern 104 for tuning a resonance frequency of the microwave resonator device 100. The tuning arrangement 110 is adapted to pass the electric current from a first point 112 of the electrically conductive line pattern 104 to a second point 114 of the electrically conductive line pattern 104.The first point

112 and the second point 114 are located a predetermined distance *d* from the open end 106, wherein the predetermined distance (*d*) is based on a length of a quarter base wavelength, λ/4.

A section 109 of the electrically conductive line pattern 104 from the first point 112 and second point 114 to the open end 106 provides an impedance converter for providing a low impedance path at the resonance frequency of the tunable microwave resonator. In fig. 1A, the electrically conductive line pattern is capacitively coupled, via capacitors 120 to a read-out transmission line 122. The open end 106 is at the capacitors 120, on the side of the capacitors not connected to the read-out transmission line 122.

Generally, a microwave resonator may be represented by a circuit including a capacitive component and an inductive component, which both contribute to the resonance behavior. Injecting the tuning electric current in to the electrically conductive line pattern 104 effectively alters the kinetic inductance, i.e. an inductive component of the electrically conductive line pattern 104, whereby the resonance frequency is altered.

Fig. 1B illustrates a voltage 139 (solid line) and current 140 (dashed line) pattern of a 3λ/4 mode of the tunable microwave resonator device conceptually shown in fig. 1A. The voltage pattern provides nodes 103, 105, where the node 105 is λ/4 away from the open end 106 of the electrically conductive line pattern 104, i.e. the same distance as from the first point 112 to the open end 106, and as the distance from the second point 114 to the open end 106. The distance 142 denotes λ/2.

During operation of the microwave resonator, 100, a microwave travels towards the open end 106 and is reflected in the opposite direction due to the high impedance presented at the open end 106. Similar to a mechanical tuning fork, a standing wave is formed, in this case a standing microwave. Due to the high impedance the electrical current is zero at the open end 106, i.e. a current node 141 is present at the open end. Thus, open end 106 of the impedance converter presents a high impendence end.

At the first and second points 112, 114, the current wave 140 is non-zero or even at maximum, and the voltage node 105 is located at or near the first and second points 112, 114. Accordingly, at the resonance frequency, the voltage 139 is zero or negligible at the first and second points 112, 114. This presents a low impedance end of the impedance converter 109, effectively providing a microwave short for the microwaves travelling in the electrically conductive line pattern 104. This provides for reducing or eliminating voltages at the first and second points 112, 114 which thereby reduces radiation losses in the tunable microwave resonator, and therefore increases the quality-factor.

Fig. 1C conceptually illustrates a tunable microwave resonator 200 according to embodiments of the present disclosure. The difference between the tunable microwave resonator 100 illustrated in fig. 1A, and the tunable microwave resonator 200 illustrated in fig. 1C is that the electrically conductive line pattern of the tunable microwave resonator 200 is inductively coupled to the read-out transmission line 122. For this, the closed end 108 is arranged towards the read-out transmission line 122.

Fig. 1D conceptually illustrates a voltage pattern of a 3λ/4 mode of the tunable microwave resonator device conceptually shown in fig. 1C. The voltage pattern provides nodes 103, 105, where the node 105 is λ/4 away from the open end 106 of the electrically conductive line pattern 104, i.e. the same distance as from the first point 112 to the open end 106, and as the distance from the second point 114 to the open end 106. For a discussion of the operation of the impedance converter 109, refer to the above description related to fig. 1B.

The read-out transmission line 122 may be supported by the substrate 102.

Referring now to figs 1A and fig. 1C in conjunction. In the example embodiments, the tuning arrangement 110 includes electrically conductive lines, e.g. terminal lines 126, 127 supported by the substrate 102 to provide the DC tuning electric current to the first point 112 and draining it at the second point 114.

In addition, as an example the tuning arrangement 110 here optionally comprises a first electrically conductive member 128 and a second electrically conductive member 129 which may be provided as e.g. electrically conductive pads, or plates, or electrical connection points. The first electrically conductive member 128, e.g. pad or plate is electrically connected to the first point 112 for providing the tuning electric current, I_T, to the first point 112 via terminal line 126. Furthermore, the second electrically conductive member 129 is electrically connected to the second point 114 for draining the tuning electric current (I_T) from the second point 114 via terminal line 127.

A DC current or power source (not shown) may be connected across the pads 128, 129 for passing the tuning current from the first point 112 to the second point 114, via the closed end 108. In other words, the tuning electric current flows along the closed end 108 of the electrically conductive line pattern 104 to tune the kinetic inductance of the material, preferably a superconductor, of the electrically conductive line pattern 104. The tuning DC electric current is adjustable such that the magnitude of the tuning DC electric current may be altered to thereby tune resonance frequency of the microwave resonator device. DC electric current or power sources are known *per se* in the art and will not be described further herein.

The tuning arrangement 110 includes connection pads, leads, or other components needed for connecting an external DC current source to the terminal lines 126, 127.

With the predetermined distance being based on a length of a quarter base wavelength (λ/4), terminal lines 126, 127 are connected a quarter base wavelength from the open end 106, close or at a voltage node of the electrically conductive line pattern 104. This reduces the residual voltage that may couple to the terminal lines 126, 127, acting as antennas, from the electrically conductive line pattern 104. The residual voltage that anyway may couple to the terminal lines 126, 127, causes radiation losses for the tunable microwave resonator device, and thus reduced quality factor, i.e. reduced performance. The residual voltages may for example be due to fabrication tolerances that causes the impedance converter 109 to be non-ideal.

Turning now to fig. 2 which illustrates the microwave resonator device 200 in fig. 1C but here with the first electrically conductive member 128 and the second electrically conductive member 129 capacitively coupled to each other as is conceptually illustrated by the capacitor 131. The capacitive coupling may be in parallel with the electrical path between the first point 112 and the second point 114 provided through the closed end 108. This reduces the radiation losses caused by the radiating terminal lines 126, 127. In particular, the capacitive coupling should be configured such that the capacitance between the first electrically conductive member 128 and the second electrically conductive member 129 provides a low impedance path at least at the resonance frequency of the tunable microwave resonator. In this way, the residual voltage between the first point 112 and the second point 114 at the resonance frequency, is further reduced or even eliminated, since the capacitive coupling provides an electrical “microwave short”.

Again, the quarter base wavelength (λ/4) section of the electrically conductive line pattern 104 serves as an impedance converter 109 which translates an infinite open end impedance at the open end 106 into near zero impedance between the first point 112 and the second point 114, thus reducing or even eliminating the voltages at the resonance frequency.

The capacitive coupling 131 lies outside of the electrically conductive line pattern 104. In other words, the first electrically conductive member 128 and the second electrically conductive member 129 are connected to each other through the electrically conductive line pattern 104 providing a DC electrical path, and the first electrically conductive member 128 and the second electrically conductive member 129 are also connected to each other via the capacitive coupling 131. Electrically, the capacitive coupling 131 is in parallel with the electrical connection provided through the electrically conductive line pattern 104 through line segments 134, 136 and the closed end 108.

In some embodiments, as will be addressed with reference to subsequent drawings, the first electrically conductive member and the second electrically conductive member may be adapted to form a capacitor in themselves.

The electrically conductive line pattern may be provided in various designs and configurations. As illustrated in e.g. fig. 2, the electrically conductive line pattern 104 comprises a first line segment 134 including the first point 112 and a second line segment 136 including the second point 114. The first line segment 134 and the second line segment 136 are connected at the closed end 108.

Although not strictly required, the first line segment 134 and the second line segment 136 are closely spaced and substantially parallel. Generally, this means that the capacitance between the first segment 134, i.e. from the first point 112 to the closed end 108, and the second segment 136, i.e. from the second point 114 to the closed end 108, is higher or significantly higher than a capacitance between any one of the segments and the ground plane of the microwave resonator device. In this way, it may be ensured that the microwave mode is localized in-between the first line segment 134 and the second line segment 136, thereby reducing parasitic resonances with e.g. a ground plane or other components of the tunable microwave resonator. Further, the capacitance per unit length of the parallel line segments is increased compared to a plain coplanar line. This further enables a relatively compact tunable microwave resonator device.

The distance between the first line segment 134 and the second line segment 136, transversely to the line segments depends on the specific design of the resonator, but may be in the range of about 10 micrometer to about 150 micrometer, such as about 20 micrometer, about 35 micrometer, about 50 micrometer, about 70 micrometer, about 90 micrometer, about 100 micrometer, etc. Note that this list is non-exhaustive.

Fig. 3A illustrates a tunable microwave resonator device 300 according to embodiments of the present invention where the electrically conductive line pattern is capacitively coupled, via a capacitor 120 to a read-out transmission line 122, and a capacitor 120 that is connected to ground via a split ground plane part 129. The tunable microwave resonator device 300 includes elements denoted with reference numerals also found in fig. 1A, if not addressed here again, refer to the above description.

In fig. 3A, the first electrically conductive member 128 is provided as a first part of a split ground plane and the second electrically conductive member 129 is provided as a second part of a split ground plane for the microwave resonator device 300. The first part 128 is electrically connected to the first point 112 by electrically conductive member 126 for providing the tuning electric current to the first point 112, and the second part 129 is electrically connected to the second point 114 by electrically conductive member 127 for draining the tuning electric current from the second point 114.

One of the capacitors 120 is connected to the read-out line 122 and the other capacitor is connected to electrical ground, here via the electrically conductive member 129.

The split ground plane parts 128 and 129 may be both connected to a shared electrical ground 152, 153, provided that the electrically conductive pattern 104, the terminal lines 126, 127, and the split ground plane parts 128 and 129 are superconducting, while couplings 150, 151 to ground from the ground plane parts 128 and 129 are non-superconducting. However, the split ground plane parts 128 and 129 may equally well be connected to individual electrical grounds 152, 153.

The first part 128 of the split ground plane is capacitively coupled to the second part 129 of the split ground plane via interdigitated capacitor structures 306. Thus, the first electrically conductive member and the second electrically conductive member are here adapted to form a capacitor and are here provided as parts of a split ground plane.

The interdigitated capacitor structures 306 between the first part of the split ground plane and the second part of the split ground plane provides a low impedance path at the resonance frequency of the tunable microwave resonator.

Fig. 3B illustrates a tunable microwave resonator 400 according to embodiments of the present disclosure. One difference between the tunable microwave resonator 300 illustrated in fig. 3A, and the tunable microwave resonator 400 illustrated in fig. 3B is that the electrically conductive line pattern 104 of the tunable microwave resonator 400 is inductively coupled to the read-out transmission line 122.

With reference to figs. 3A-B, the split ground plane includes the first part 128 that is capacitively coupled to the second part 129 of the split ground plane via interdigitated, e.g. comb-shaped, capacitor structures 306. Thus, the first part 128 includes one side of each of the capacitor structures 306 and the second part includes the other side of each of the capacitor structures 306. Each of the sides are formed to interdigital match the other side, to thereby form an interdigitated capacitor 306.

The split ground plane parts 128, 129 may advantageously be located in the same plane as the electrically conductive line pattern 104.

However, the split ground plane parts 128, 129 may be located in a different plane than the electrically conductive line pattern 104. In such case, the split ground plane parts 128, 129 may be connected to the first point 112, and the second point 114 by e.g. vertical interconnect access (VIA), through e.g. layers of the tunable microwave resonator or the substrate 102 depending on the specific implementation.

In accordance with embodiments, the electrically conductive line pattern may be planar. In other words, the electrically conductive line pattern may be made in a single plane on the dielectric substrate.

The tunable microwave resonator may be manufactured by thin film technology. Thin film technology includes various techniques known per se to the skilled person, such as electron beam lithography, photolithography sputtering, chemical vapor deposition, physical vapor deposition, pulsed laser deposition, etc. A typical film thickness is in the range of 10 nm to 500 nm.

The electrically conductive line pattern and other electrically conductive elements of the tunable microwave resonator may be made from a metal material.

Preferably, the electrically conductive line pattern is made from a superconductor material. Further, the terminal lines, the electrically conductive members 128, 129, any other electrically conductive parts of the tunable microwave resonator device may be made from a superconductor material. The specific superconductor material may be selected based on a specific implementation.

A wide range of superconductors are known *per se* to the skilled person. Purely for example purposes, example superconductors may be niobium-based superconductors (e.g. niobium, niobium-nitride, niobium-tin, Niobium-titanium, niobium-germanium, niobium-aluminum), ceramic or cuprate superconductors (e.g. YBCO, NBCO, BSCO, etc..), iron-based superconductors, or other compound (e.g. covalent superconductors) superconductors or single element superconductors. The above example superconductors represent a non-exhaustive list of superconductors that may be applicable to embodiments presented herein.

Using a superconducting material for the electrically conductive line pattern provides for efficient tuning of the kinetic inductance of the electrically conductive line pattern by injecting a tuning DC or AC current. The microwave resonator device is operated when the superconductor material is in the superconducting state.

The tunable microwave resonator device according to embodiments of the present invention may be used for various applications, such as filters in telecommunications applications and qubit communication buses for quantum computers.

The size of the tunable microwave resonator device depends on the specific implementation and is adapted to microwave electronics. Thus, the line width of the electrically conductive line pattern may be in the order of micrometers such as for example 1, 2, 3, 4, 5, 6, 7, 10, 15 micrometer, or below a micrometer, such as a fraction of a micrometer.

The person skilled in the art realizes that the present invention by no means is limited to the preferred embodiments described above. On the contrary, many modifications and variations are possible within the scope of the appended claims.

For example, the specific shape of the electrically conductive line patterns is herein depicted in a U-shape. However, the outline of the electrically conductive line pattern may take other forms, such as with nonparallel line segments, with turns in the line segments, with sharp corners resembling an open rectangular shape, etc.

In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

CLAIMS

1. A tunable microwave resonator device (100, 200, 300, 400) having an associated base wavelength, the microwave resonator device comprising:

a dielectric substrate (102);

an electrically conductive line pattern (104) supported by the dielectric substrate, the electrically conductive line pattern having an open end (106) and a closed end (108),

a tuning arrangement (110) adapted to provide a tuning electric current (I_T) into the electrically conductive line pattern for tuning a resonance frequency of the microwave resonator device, the tuning arrangement is adapted to pass the electric current from a first point (112) of the electrically conductive line pattern to a second point (114) of the electrically conductive line pattern via the closed end,

wherein the first point and the second point are located a predetermined distance (*d*) from the open end, wherein the predetermined distance is approximately, or equal to, a quarter base wavelength.

2. The tunable microwave resonator according to claim 1, wherein a section (109) of the electrically conductive line pattern from the first and second point to the open end is configured as an impedance converter for providing a low impedance path at the resonance frequency of the tunable microwave resonator.

3. The tunable microwave resonator device according to any one of the preceding claims, wherein the first point and the second point are at a respective location associated with a voltage node (105) of the tunable microwave resonator.

4. The tunable microwave resonator device according to any one of the preceding claims, wherein the tuning electric current is injected through the first point and drained through the second point.

5. The tunable microwave resonator device according to any one of the preceding claims, comprising a first electrically conductive member (128) and a second electrically conductive member (129), wherein the first electrically conductive member is electrically connected to the first point for providing the tuning electric current to the first point, and the second electrically conductive member is electrically connected to the second point for draining the tuning electric current from the second point.

6. The tunable microwave resonator device according to claim 5, wherein the first electrically conductive member (128) and the second electrically conductive member (129) are capacitively coupled to each other.

7. The tunable microwave resonator device according to claim 6, wherein the first electrically conductive member and the second electrically conductive member are adapted to form a capacitor.

8. The tunable microwave resonator device according to any one of claims 6 and 7, wherein the capacitive coupling between the first electrically conductive member and the second electrically conductive member provides a low impedance path at the resonance frequency of the tunable microwave resonator.

9. The tunable microwave resonator device according to any one of the preceding claims, wherein the electrically conductive pattern comprises a first line segment (134) including the first point and a second line segment (136) including the second point, wherein the first line segment and the second line segment are connected at the closed end.

10. The tunable microwave resonator device according to claim 9 wherein the first line segment and the second line segment are substantially parallel.

11. The tunable microwave resonator device according to any one of the preceding claims, comprising electrically conductive lines (126, 127) supported by the substrate for connecting a DC current source to the first point and the second point.

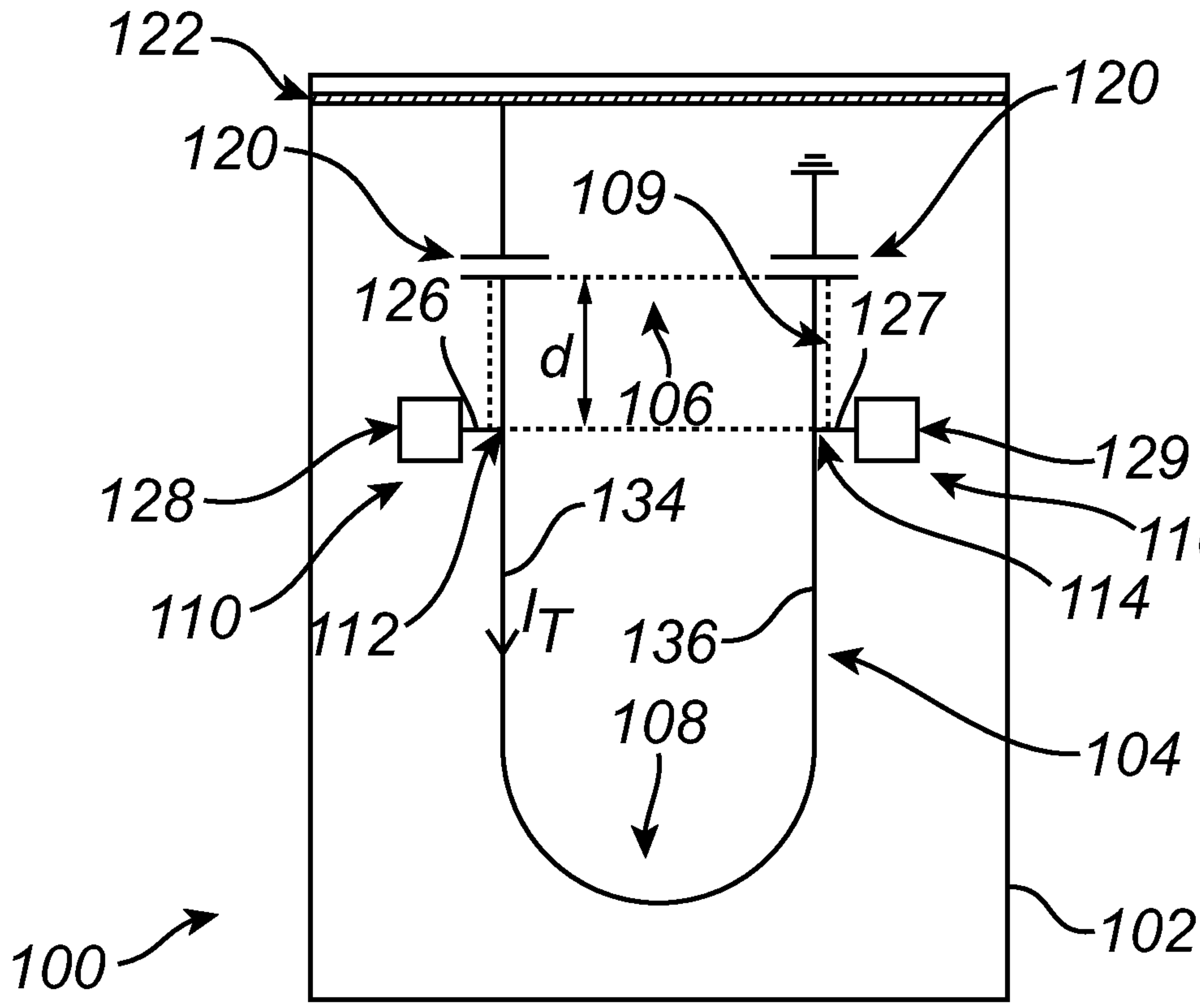
12. The tunable microwave resonator device according to any one of the preceding claims, adapted to be capacitively or inductively coupled to a read-out transmission line.

13. The tunable microwave resonator device according to claim 12, wherein the read-out transmission line is supported by the dielectric substrate.

14. The tunable microwave resonator device according to any one of the preceding claims, wherein the electrically conductive line pattern is planar.

15. The tunable microwave resonator device according to any one of the preceding claims, manufactured by thin film technology.

16. The tunable microwave resonator device according to any one of the preceding claims, wherein the electrically conductive line pattern is made from a superconductor material.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120
120
109
126
127
d
106
128
129
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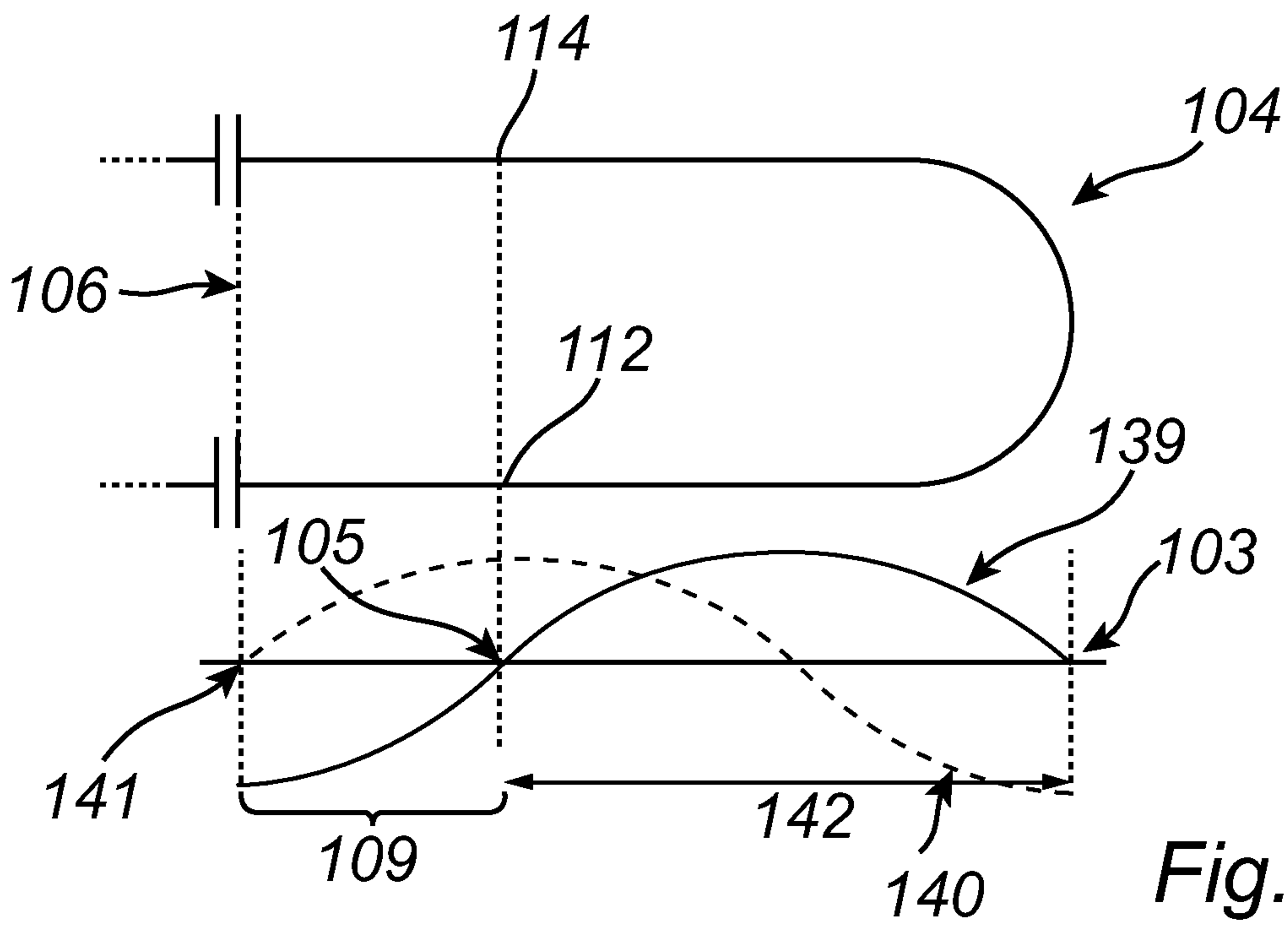
134
110
112
I_T
114
136
108
104
102
100

Fig. 1A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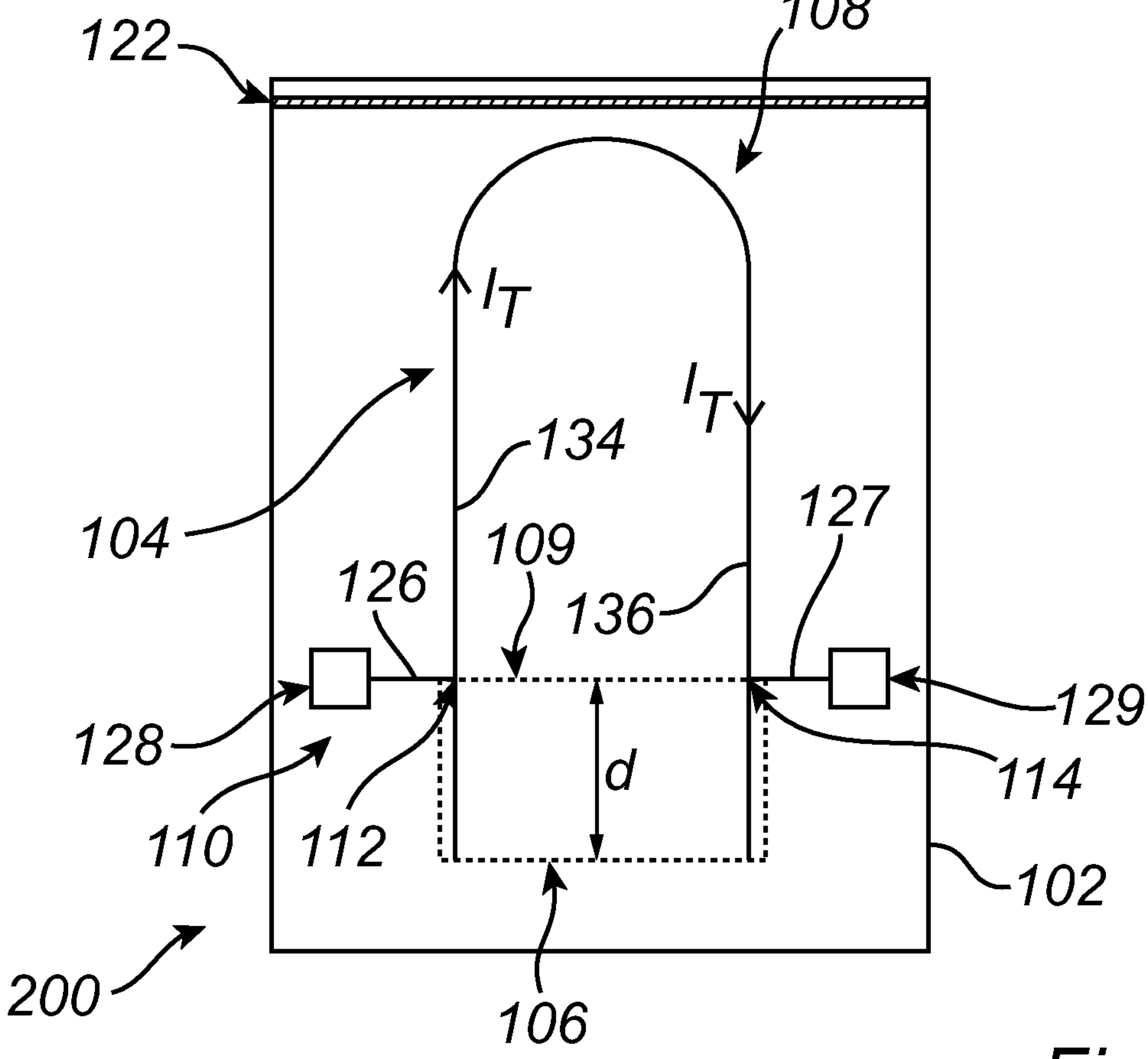
104
106
112
139
105
103
141
142
109
140

Fig. 1B



122
108
I_T
I_T
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136
128
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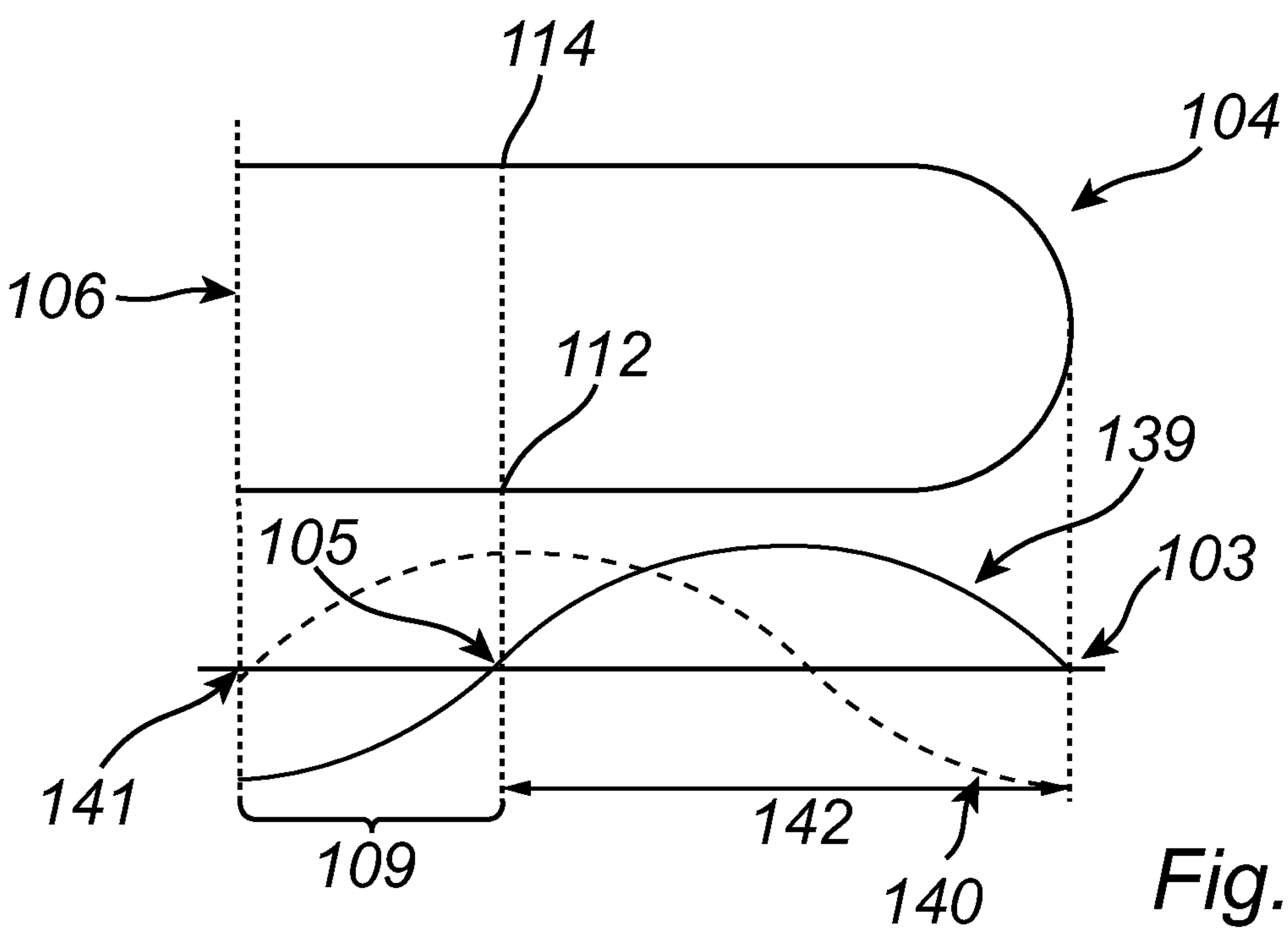
200
106

Fig. 1C



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142
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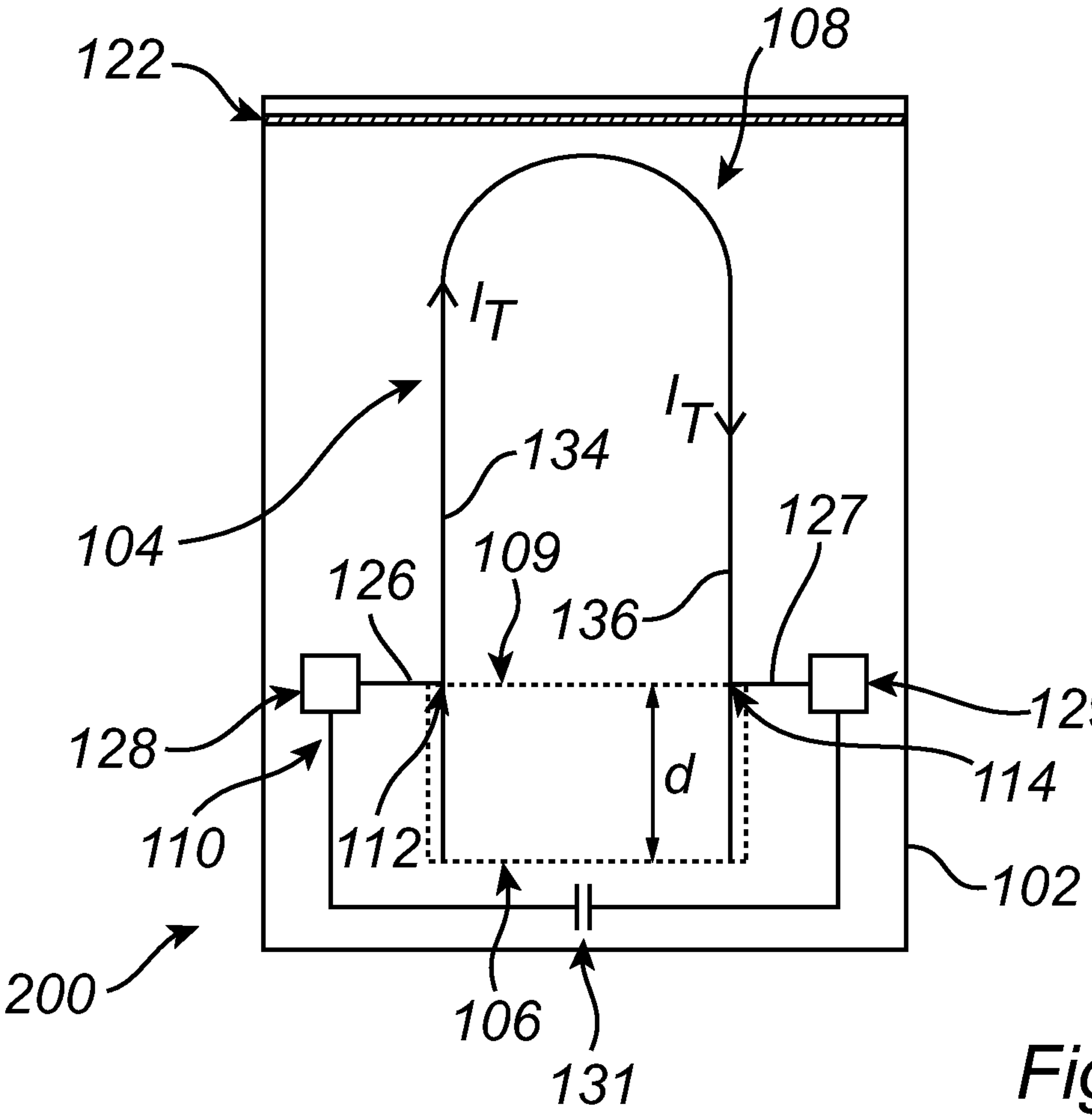
140

Fig. 1D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I_T
I_T
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136
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129
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d
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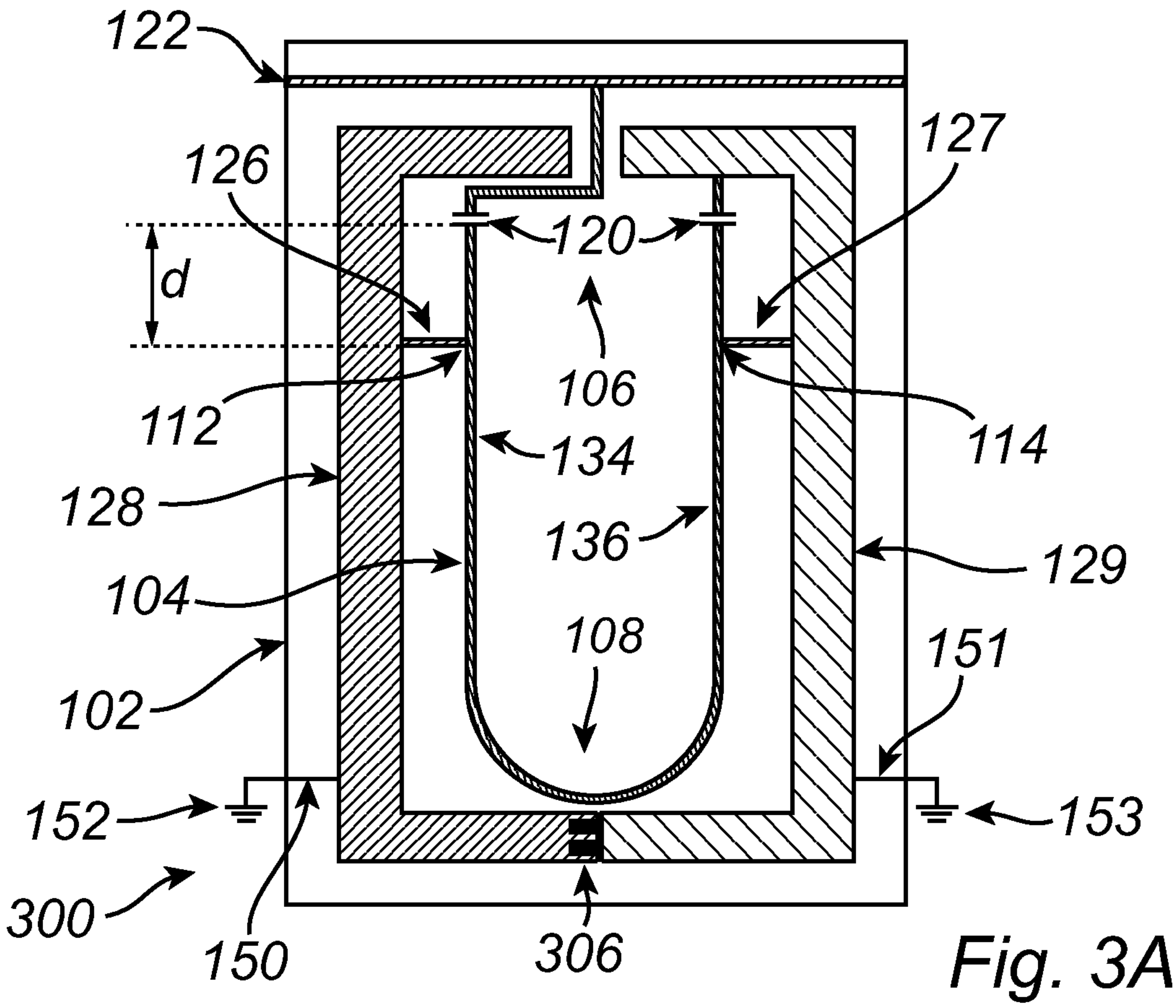
102
200
106
131

Fig. 2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127
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153
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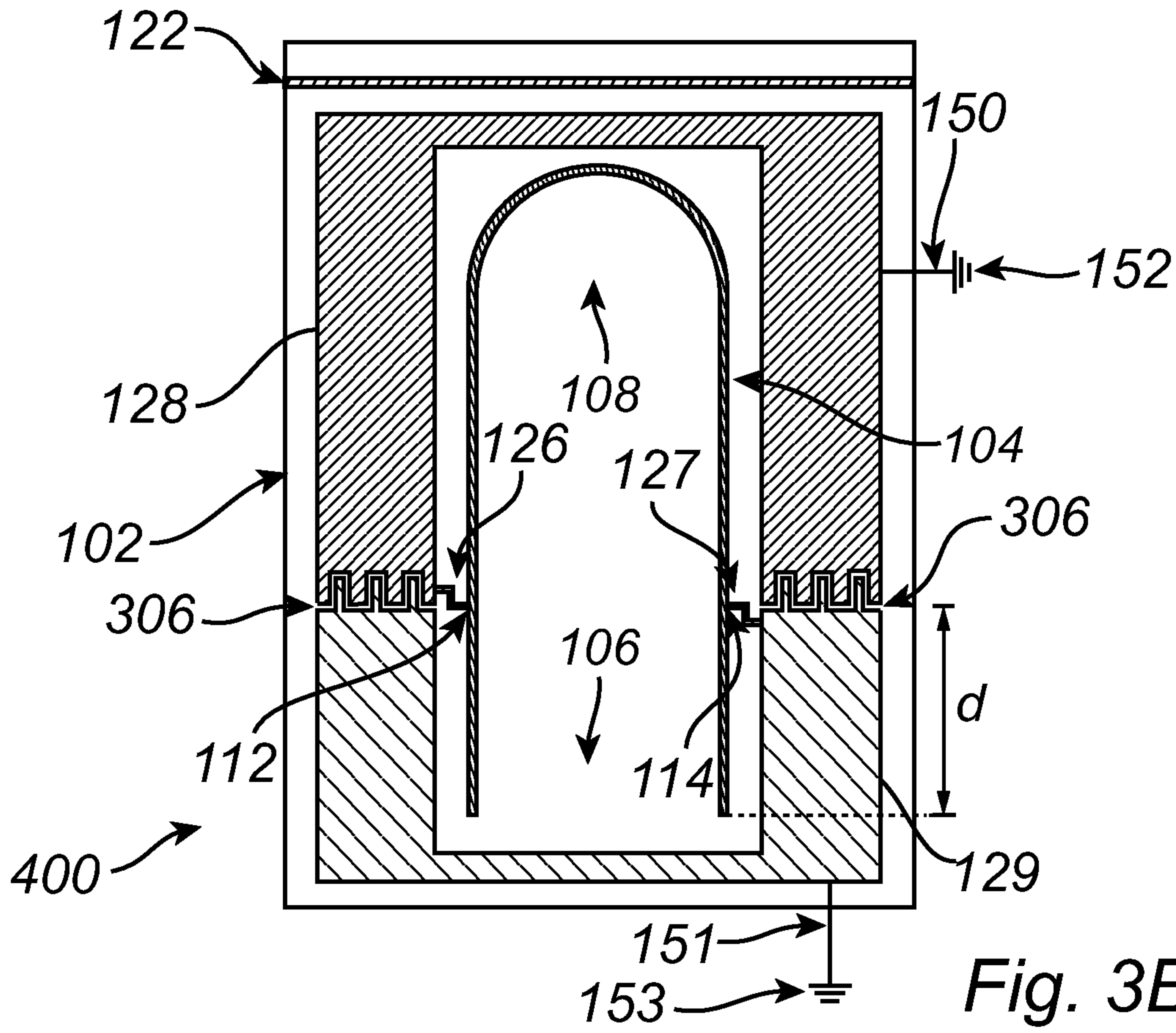
306

Fig. 3A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128
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127
102
306
306
106
d
112
114
400
129
151
153

Fig. 3B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2020/051193

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: H01L, H01P

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE, DK, FI, NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, PAJ, WPI data, COMPENDEX, INSPEC, IBM-TDB, Internet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	S. E. de Graaf et al., "Galvanically split superconducting microwave resonators for introducing internal voltage bias", Applied Physics Letters, vol. 104, 052601 (2014); DOI: 10.1063/1.4863681; whole document --	1-16
A	M. Sandberg et al., "Fast tuning of superconducting microwave cavities", AIP Conference Proceedings 1074, 12 (2008); DOI: 10.1063/1.3037127; abstract; figure 1; section "THE TUNABLE CAVITY" --	1-16

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29-01-2021	01-02-2021
Name and mailing address of the ISA/SE Patent- och registreringsverket Box 5055 S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86	Authorized officer Erik Eriksson Telephone No. + 46 8 782 28 00

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	F. Chen et al., "Introduction of a dc bias into a high-Q superconducting microwave cavity", Applied Physics Letters, vol. 98, 132509 (2011); DOI: 10.1063/1.3573824; abstract; page 1; figure 1 --	1-16
A	S.-X. Li and J. B. Kycia, "Applying a direct current bias to superconducting microwave resonators by using superconducting quarter wavelength band stop filters", Applied Physics Letters, vol. 102, 242601 (2013); DOI: 10.1063/1.4808364; abstract; figures 3-4 --	1-16
A	US 6097263 A (MUELLER CARL H ET AL), 1 August 2000 (2000-08-01); column 8, line 29 - line 57; figure 3 --	1-16
A	US 5888942 A (MATTHAEI GEORGE L), 30 March 1999 (1999-03-30); abstract; figures 1,9A --	1-16
A	US 20020158719 A1 (LIANG XIAO-PENG ET AL), 31 October 2002 (2002-10-31); abstract; figure 2 --	1-16
A	EP 1575119 A1 (UNIV TSINGHUA), 14 September 2005 (2005-09-14); abstract; paragraphs [0014]-[0018]; figure 4 --	1-16
T	S. Mahashabde et al., "Fast tunable high Q-factor superconducting microwave resonators", https://arxiv.org/abs/2003.11068v1 (2020-03-24); whole document -- --------	1-16

Continuation of: second sheet

International Patent Classification (IPC)

H01P 7/08 (2006.01)
H01P 1/203 (2006.01)
H01L 39/08 (2006.01)

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