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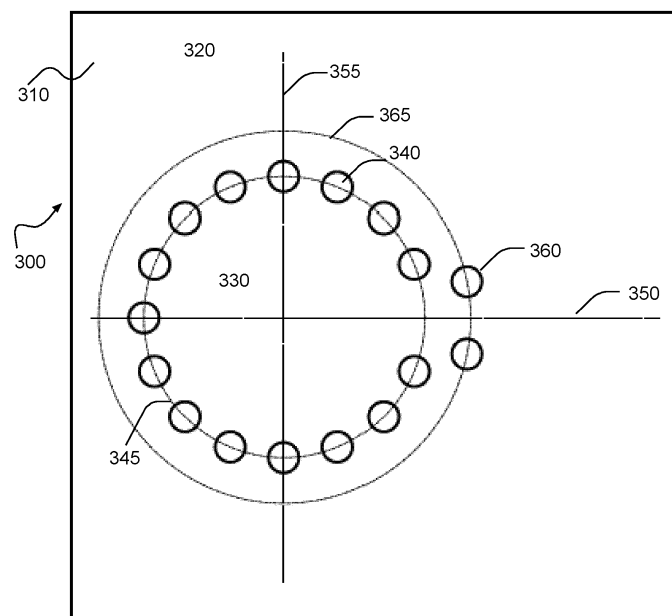
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(54) SUPERCONDUCTING MICROWAVE DEVICE FOR HOSTING QUBITS

(57) A superconducting microwave device for hosting qubits comprises a substantially planar substrate (310, 710, 1110) coated with a superconducting metal, wherein said substantially planar substrate (310, 710, 1110) comprises a plurality of through-holes (340, 740, 1140), said plurality of through-holes being arranged to define a first contour (345, 745, 1145) which divides said substantially planar substrate (310, 710, 1110) into a resonator portion (330, 730, 1130) enclosed within said first contour (345, 745, 1145) and a machining portion

(320, 720, 1120) comprising a holding area for maintaining said superconducting qubit device (300, 700, 1100) during the substantially planar substrate superconducting metal coating, said through-holes (340, 740, 1140) being arranged about said first contour (345, 745, 1145)

such that $4 > \frac{s}{d} > 1$ where s is the inter-through-hole spacing and d is the through-hole diameter.

**Fig.3**

Description

[0001] The invention concerns a superconducting device design using a substrate integrated resonator in the microwave band. This type of device is used for hosting (or storing, the two terms are interchangeable) and interacting with qubits, whether classic, based on a bosonic code or otherwise.

[0002] In the known state of the art, such superconducting devices are generally divided into two categories: 2D planar superconducting microwave resonators patterned in a thin metal layer on top of a dielectric substrate, and 3D superconducting microwave resonators where the resonator is defined as a cavity filled with vacuum dug in a bulk of superconducting metal, typically aluminum or niobium.

[0003] The quality factor of resonators is a very important feature for qubit hosting resonators, as the quality factor Q relates to the ratio of the resonance frequency ω of the resonator to the single photon loss rate κ_1 as shown by the following equation: $Q = \omega/\kappa_1$.

[0004] In 2D planar superconducting microwave resonators, the electromagnetic field used to implement the qubits is located at the substrate-air interface with a thin superconducting metal layer.

[0005] In 2D planar superconducting microwave resonators (also called 2D resonators in the following), the imperfections of the fabrication process lead to the substrate-air interface carrying impurities which produce important electromagnetic losses.

[0006] As a result, the state-of-the-art quality factor in the 2D planar geometry is of the order of 10^6 to 10^7 . The cleanliness of the substrate-air interface of 2D planar superconducting microwave resonators is the limiting factor of their performance as quantum memories.

[0007] In order to improve quality factor of 2D resonators, current approaches focus on decreasing the 2D planar superconducting microwave resonator intrinsic loss. These approaches generally focus on decreasing the participation of the electric field in the impurities at the substrate-air, metal-air and substrate-metal interface. One way to achieve that low participation is to get rid of most of the impurities by partially chemically etching the dielectric substrate below the superconducting resonator. That method is only available for silicon based superconducting circuits and is impossible with a sapphire substrate. Also, this does not tackle the metal-air interface imperfections.

[0008] In 3D superconducting microwave resonators (also called 3D resonators in the following), the electromagnetic field is stored inside the volume. The quality factors of 3D resonators are typically 10^7 to 10^8 , meaning they are at first sight more interesting for quantum memories than 2D resonators.

[0009] The downside is that 3D resonators are bulky with respect to 2D resonators, typically several centimeters wide, and filled with vacuum. The volume of those superconducting resonators does not allow them to be

integrated in larger or more complex superconducting quantum circuit architectures.

[0010] Moreover, the coupling with nanometer scale metallic structures is difficult because there is a need to build a mechanical assembly, something in clear contrast with the 2D resonators. In 3D resonators, the planar superconducting structure needs to be introduced mechanically inside the cavity to achieve a coupling. Finally, due to the Meissner effect, the 3D resonators prevent the fine tuning of the superconducting assembly parameters with external magnetic fields. This is again in clear contrast with the 2D resonators where external magnetic fields can easily be applied to fine tune the electrical system properties.

[0011] Consequently, scalability and integrability properties are the biggest current limitations of 3D resonators.

[0012] The conventional 3D resonators are typically 3cm*3cm*5cm and have a shape as shown on Figure 1. This cross-sectional view shows that the resonator has a generally cylindrical shape. The body of the cylinder is made of superconducting metal, and the inside of the cylinder is vacuum, except for a central protrusion also made of superconducting metal. This central protrusion is where the electromagnetic field hosted by the resonating modes is located. The vacuum around it aims at limiting the dielectric loss by providing the cleanest environment to the electric field.

[0013] Notwithstanding its dimensions, this design has the disadvantage of necessitating the inclusion of a conducting line in order to introduce external magnetic field inside the cavity in order to generate and to interact with the qubit. Conventionally, this conducting line protrudes radially from the exterior through the cylinder wall towards the protrusion. The manner in which this conducting line is introduced in the system generally damages the quality of the electromagnetic field confinement and thus structurally limits the Q factor values that can be achieved. The articles <https://arxiv.org/abs/1508.05882> and <https://aip.scitation.org/doi/10.1063/5.0016463> show examples of how to realize such a type of resonators.

[0014] In order to improve the footprint of 3D resonators, micromachined superconducting cavities have been proposed which are millimetric (typically 15mmx15mmx2mm), as shown on Figure 2. These 3D resonators are made of two superconducting parts: a bottom part made of a silicon substrate etched as a pit covered with superconducting metal and a top part made of silicon substrate covered with a superconducting metal. The top and bottom parts need to be joined together by superconducting solders, typically bumps made of indium (schematically shown on Figure 2 by a square with crossing diagonals). The soldering step requires a complex manipulation of the two superconducting parts. The issue related to external magnetic field application remains. Moreover, the electric field is mostly concentrated in the vacuum in the middle of the 3D cavity, but its value remains non negligible on the edges of the enco-

sure. It participates a bit in the lossy several nanometer thick dielectric layer which is grown on top of the superconducting metal capping during the fabrication of the device. Integrability still remains a significant challenge in the application to quantum circuits. The article <https://arxiv.org/abs/2001.09216> shows an example of how to realize such a type of resonators.

[0015] Another theoretical approach could be to have a resonator made of a sapphire or silicon substrate fully coated with a superconducting metal. Using the sub-

strate instead of vacuum would allow to gain a $\sqrt{\epsilon_r}$ dimension factor, potentially reducing the dimensions to 10mm*10mm*1mm. However, this theoretical approach suffers from the incurable flaw that the superconducting metal must be deposited on the substrate to perform the coating. That would require a way to maintain the substrate without any point of contact as the depositing is made by vaporizing the superconducting metal. Hence, it is currently impossible to manufacture a 3D resonator according to this approach in a single coating step. If one was to attempt two steps coating, the electric contact between the two metal layers would remain an issue, and the contact area in between the 2 metal layers will be the limiting factor of the resonator quality factor.

[0016] The invention aims at improving the situation. To this end, the Applicant proposes a superconducting microwave device for hosting qubits comprising a substantially planar substrate coated with a superconducting metal, wherein said substantially planar substrate comprises a plurality of through-holes, said plurality of through-holes being arranged to define a first contour which divides said substantially planar substrate into a resonator portion enclosed within said first contour and a machining portion comprising a holding area for maintaining said superconducting qubit device during the substantially planar substrate superconducting metal coating, said through-holes being arranged about said

$$4 > \frac{s}{d} > 1$$

first contour such that where s is the inter-through-hole spacing and d is the through-hole diameter.

[0017] This superconducting microwave device for hosting qubits is advantageous because it proposes a millimetric size 3D resonator which can actually be manufactured reliably and which also provides for easier application of external magnetic field.

[0018] In various embodiments, the superconducting microwave device may present one or more of the following features:

- the resonator portion has a resonance frequency

which is less than $f_m = \frac{c}{4s\sqrt{\epsilon_r}}$, where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate,

- the resonator portion comprises a blind hole,

- the resonator portion comprises a second plurality of through-holes defining a second contour, wherein the through-holes defining said second contour have dimensions of diameter and inter-through-hole spacing substantially identical to those of said first contour,
- the machining portion further comprises a third plurality of through-holes arranged such that $\frac{s_p}{d_p} > 1$

where s_p is the maximum inter-through-hole spacing for the third plurality of through-holes and d_p is the third plurality of through-holes diameter, whereby only parasite electromagnetic modes having a frequency of more than

$f_p = \frac{c}{2s_p\sqrt{\epsilon_r}}$ will be allowed in the machining portion, where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate, and

- said plurality of through-holes are arranged to define a plurality of first contours which divide said substantially planar substrate into respective resonator portions each enclosed within a respective one of said first contours and said machining portion.

[0019] The invention also concerns a method of fabricating a superconducting microwave device for hosting qubits comprising the following operations:

- a) providing a substantially planar substrate,
- b) providing a plurality of through-holes in said substantially planar substrate, said plurality of through-holes being arranged to define a first contour which divides said substantially planar substrate into a resonator portion enclosed within said first contour and a machining portion, said through-holes being arranged about said first contour such that

$$4 > \frac{s}{d} > 1$$

where s is the inter-through-hole spacing and d is the through-hole diameter, and

- c) coating the substantially planar substrate of operation b).

[0020] This method is advantageous because it allows to make a superconducting microwave device for hosting qubits according to the invention.

[0021] In various embodiments, the method may present one or more of the following features:

- the method further comprises operation d) engraving circuit design elements by providing a circuit mask on the substantially planar substrate of operation c) and etching,
- operation b) provides a resonator portion having a resonance frequency which is less than

$$f_m = \frac{c}{4s_p \sqrt{\epsilon_r}}$$

, where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate,

- operation b) further comprises providing a blind hole in said resonator portion,
- operation b) further comprises providing the resonator portion with a second plurality of through-holes defining a second contour, wherein the through-holes defining said second contour have dimensions of diameter and inter-through-hole spacing substantially identical to those of said first contour,
- operation b) further comprises providing the machining portion with a third plurality of through-holes ar-

$$\frac{s_p}{d_p} > 1$$

ranged such that where s_p is the maximum inter-through-hole spacing for the third plurality of through-holes and d_p is the third plurality of through-holes diameter, whereby only parasite electromagnetic modes having a frequency of more than

$$f_p = \frac{c}{2s_p \sqrt{\epsilon_r}}$$

will be allowed in the machining portion, where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate,

- operation c) comprises:
 - c1) holding the substantially planar substrate by a corner of said machining portion in a coating chamber,
 - c2) making vacuum in said coating chamber,
 - c3) vaporizing metal in said coating chamber while orienting said substantially planar substrate about a plurality of different angles in the flow of vaporized metal,
 - c4) rotating the substantially planar substrate by 180° without breaking the vacuum of said coating chamber, and
 - c5) vaporizing metal in said coating chamber while orienting said rotated substantially planar substrate about a plurality of different angles in the flow of vaporized metal, and
- operation b) comprises providing a plurality of through which are arranged to define a plurality of first contours dividing said substantially planar substrate into respective resonator portions each enclosed within a respective one of said first contours and said machining portion.

[0022] Other features and advantages of the invention will readily appear in the following description of the drawings, which show exemplary embodiments of the invention and on which:

- Figure 1 shows a generic design of a known con-

ventional 3D resonator,

- Figure 2 shows a generic design of another known 3D resonator,
- Figure 3 shows a top view of a first embodiment of 3D resonator according to the invention,
- Figure 4 shows a bottom view of the embodiment of Figure 3,
- Figure 5 shows a cross-sectional view of Figure 3 along line V-V of Figure 4,
- Figure 6 shows a microwave simulation of the electromagnetic field in the device of Figure 3,
- Figure 7 shows a top view of a second embodiment of 3D resonator according to the invention,
- Figure 8 shows a bottom view of the embodiment of Figure 7,
- Figure 9 shows a cross-sectional view of Figure 6 along line IX-IX of Figure 8,
- Figure 10 shows a microwave simulation of the electromagnetic field in the device of Figure 7,
- Figure 11 shows a top view of a third embodiment of 3D resonator according to the invention,
- Figure 12 shows a bottom view of a the embodiment of Figure 11,
- Figure 13 shows a cross-sectional view of Figure 6 along line XIII-XIII of Figure 12,
- Figure 14 shows a microwave simulation of the electromagnetic field in the device of Figure 11,
- Figure 15 shows a diagram of a manufacturing method of a superconducting microwave device of Figures 3 to 14,
- Figure 16 shows a picture of three 3D resonators manufactured according to the method of Figure 15 after the superconducting metal has been deposited, and
- Figure 17 shows a picture of a 3D resonator according to the invention fully packaged to be included in a quantum circuit, and
- Figure 18 shows a schematic diagram of a 3D resonator according to the invention comprising several resonator portions.

[0023] The drawings and the following description are comprised for the most part of positive and well-defined features. As a result, they are not only useful in understanding the invention, but they can also be used to contribute to its definition, should the need arise.

[0024] Figure 3 shows a top view of a first embodiment of 3D resonator 300 according to the invention. The resonator 300 is realized on a substantially parallelepiped substrate 310 having exemplary dimensions of 10mm*10mm*1mm. In various embodiments, the substrate 310 may have a thickness less than 1mm and be typically any value which is more or equal to 0.1mm.

[0025] This substrate is typically made of c-oriented sapphire which has a dielectric permittivity $\epsilon_r = 11.3$ at cryogenic temperature along the c-axis (isotropic). This type of sapphire can be obtained by various growth methods such as HEM (Heat Exchanger Method), Kyr-

opoulos, EFG or Czochralski. The article <https://www.gia.edu/gia-news-research-Sapphire-Series-Next-Generation-Growth-Techniques> offers further information.

[0026] The substrate may also be made of silicon which has a dielectric permittivity $\epsilon_r = 11.45$ at cryogenic temperature. This type of silicon can be obtained by various growth methods such as Czochralski (called "CZ") and FloatZone (called "FZ"). The article https://meroli.web.cern.ch/Lecture_silicon_floatzone_czochralski.html offers further information.

[0027] As shown on Figure 3, a superconducting microwave device 300 according to a first embodiment of the invention comprises two zones: a machining portion 320 and a resonator portion 330 in which the electromagnetic field remains confined.

[0028] It should be noted that this idea is not as trivial as it may appear. First of all, none of the existing technologies provide for a machining portion and a resonator portion distinct from one another.

[0029] Thus, this difference in itself is extremely novel.

[0030] Furthermore, while the idea of providing a manufacturing portion to allow manipulation of the substrate to properly deposit the superconducting metal on its surface appears appealing, it still requires providing a way to define the resonator portion in such a manner that it confines the electromagnetic field.

[0031] The most immediate way to do this would be to define a contour of vacuum in the substrate which would define the resonator portion. However, the manufacturing of sapphire substrate is extremely delicate, and digging the substrate is extremely difficult. It is even more so to achieve a near perfectly polished surface as is necessary for the device to function properly.

[0032] In order to solve this problem, the Applicant had the idea to use substrate integrated waveguide technologies and of using Faraday cage like properties instead of a continuous vacuum contour to define the resonator portion.

[0033] As appears on Figure 3, the Faraday cage is realized by a plurality of through-holes 340 which are substantially aligned along a contour line 345. This contour line is purely symbolic and is provided on Figure 3 to show how the through-holes 340 are aligned.

[0034] In order to implement the Faraday cage effect, the through-holes have to respect at least some of the following properties:

a) $4 > \frac{s}{d} > 1$ where s is the inter-hole spacing and d is the hole diameter,

b) $\frac{\lambda}{4} > s$ where λ is the wavelength of an electromagnetic mode confined in the resonator due to the Faraday cage effect.

[0035] Condition a) is indispensable as it guarantees

the avoidance of radiative losses and holes overlap.

Condition b) is important because $\frac{\lambda}{4} > s$ allows to avoid bandgap within the single mode band SIW.

[0036] In view of the above, and taking into account that qubit resonating modes have a frequency generally comprised between 1GHz and 20GHz, the following parameters can be considered, in view of the fact that

$$f = \frac{c}{\lambda \sqrt{\epsilon_r}} \text{ where } c \text{ is the speed of light in the vacuum.}$$

f (GHz)	λ (mm)	s max (mm)
1	89	22.3
4	22	5.57
7	12.7	3.19
10	8.9	2.23
12	7.43	1.86

[0037] Another way to analyze equation b) is that, for a given value of s, the Faraday cage effect will be achieved for electromagnetic modes in the resonator portion hav-

ing a frequency which is less than $f_m = \frac{c}{4s\sqrt{\epsilon_r}}$. Thus, the electromagnetic modes within the resonator portion with such frequencies will have a high quality factor.

[0038] Like contour 345, axis 350 and 355 are provided to show the symmetry of the through-holes arrangement defining the resonator portion 330. In Figure 3, the resonator portion 330 is not centered on the substrate 310. In other embodiments, it can be centered. Furthermore, in the embodiment shown here, the contour 345 lacks one through-hole 340 which is opposite to the through-hole centered on axis 350. This absence allows for the possibility to introduce a transmission line not shown on this figure which is surrounded by two supplementary through-holes 360 which are aligned along a second contour line 365 in order to prevent the electromagnetic field to leak out. In alternative embodiments, the through-holes 360 could be omitted, and the lacking through-hole 320 could be added back. In this case, the transmission line will have to be brought otherwise, possibly from the underside of the superconducting microwave device 300.

[0039] Figure 4 shows a bottom view of the superconducting microwave device of Figure 3, and Figure 5 shows a cross sectional view along axis V-V of Figure 4. Figure 4 and Figure 5 show that a central portion of the resonator portion 330 has been dug to provide for a blind hole 370.

[0040] The blind hole 370 reduces the thickness of the substrate portion housing the electromagnetic field, which allows to uncouple the inductance and the capa-

citance of the resonator.

[0041] Indeed, the capacitance (C) is proportional to the area, i.e. the metal disks, that are on top of each other spaced by the dielectric material. With the blind hole, for a given spacing, there is a well-defined capacitance. If there is no blind hole, the capacitance of the resonator is defined by the full disk defining the resonator portion instead of a portion thereof. With the blind hole, the fact that the disks are smaller tends to reduce the capacitance, but the closeness of the disks tends to increase the capacitance. By designing the blind hole properly, the capacitance value can thus be controlled.

[0042] Moreover, the inductance (L) of the resonator is defined as the electrical length separating the top face from the bottom face. Since the resonance frequency of

an electrical resonator is given by $2\pi/\sqrt{LC}$. In the absence of the blind hole, only changing the diameter of the resonator portion allows to control the resonance frequency. Uncoupling L and C with the blind hole allows to change the frequency of the resonator without needing to change the diameter of the resonator. Indeed, for a given diameter of the resonator portion, changing the depth of the blind hole will affect the value of the capacitance much more than the value of the inductance, thus allowing to change the resonance frequency. Thus, uncoupling the inductance and the capacitance allows to maintain the footprint while tuning the resonance frequency.

[0043] In some embodiments, the blind hole 370 could be omitted. On Figure 4, additional lines have been added to show how through-holes 340 and 360 are respectively arranged about contour lines 345 and 365 respectively.

[0044] Figure 6 shows a microwave simulation of the electromagnetic field in the device of Figure 3. As appears on this figure, the electromagnetic field is confined within the resonator portion 330 and does not escape it.

[0045] This is fundamental because it shows the great advantage of the invention. Since the electromagnetic field is confined within the resonator portion 330, the machining portion 320 can be handled in any manner needed or wanted. This is very interesting because of the process used to coat the substrate 310 with the superconducting metal.

[0046] Indeed, the superconducting metal is deposited in an evaporator, by coating the sample with vaporized metal. Because the machining portion 320 can be freely manipulated, it is possible to grab the substrate 310 comprising the resonator portion with a clamp which is mounted about a rotating arm. In this manner, the substrate 310 can be rotated so that the surface of the substrate 310 and the inside of the through-holes 320 is properly coated, except where the clamp holds the machining portion 320. Thus, the whole of the substrate 310 can be evenly coated with superconducting metal, except at the holding portion. But that has no negative consequence, since the resonator portion 330 design

allows to confine the electromagnetic field within it.

[0047] Figures 7, 8, 9 and 10 respectively correspond to Figures 3, 4, 5 and 6, but with a superconducting microwave device 700 according to a second embodiment of the invention. Like elements will have the same two last digits of the references numerals of Figures 3, 4, 5 and 6, and only the differences will be described for the sake of simplicity. As a result, on Figures 7, 8, 9 and 10, the machining portion is referenced 720, and the resonator portion is referenced 730, etc.

[0048] As appears on these figures, supplementary through-holes 740 have been added along contour line 765 to further confine the electromagnetic field, and also to protect the resonator portion 730 from external fields. Furthermore, additional through-holes 380 have been added on each side of axis 750 to further confine the field within the transmission line to be engraved. On Figures 7 and 8, through-holes 760 and 770 clearly appear as a sort of "field guide" for the transmission line.

[0049] Figures 11, 12, 13 and 14 correspond to Figures 7, 8, 9 and 10, but with a superconducting microwave device 1100 according to a third embodiment of the invention. Like elements will have the same two last digits of the references numerals of Figures 7, 8, 9 and 10, and only the differences will be described for the sake of simplicity. As a result, on Figures 11, 12, 13 and 14, the machining portion is referenced 1120, and the resonator portion is referenced 1130, etc.

[0050] The main differences between these two embodiments is that transmission line pathways have been provided symmetrically to one another with through-holes 1180, and that through-holes 1190 have been added in the machining portion 1120.

[0051] The role of the through-holes 1190 is to control the frequency of parasite modes which may develop in the machining portion 1120. By choosing carefully the inter-hole distance between through-holes 1190, the frequency of parasite modes can be brought to several ten of GHz, thereby preventing any perturbation in practice. Through-holes 1190 further present the advantage of ensuring that both sides of the substrate have the same potential in all part of the machining portion after the engraving of the chip is performed. Indeed, the engraving is performed by superposing a mask of the features to be engraved on the coated surface and subsequent coating. This action can typically result in some parts of the substrate in the machining portion be electrically isolated from others. However, the through-holes 1190 cannot get fully etched and hence guarantee electrical continuity in several parts of the machining portion 310 between the two opposite faces.

[0052] It should be noted that the second row of through-holes 1190 in the triangle shape arrangement of through-holes 1190 in each corner of substrate 1110 could be removed, as it is the inter-hole distance between the holes 1190 centered on axis 1155 and the nearest through-hole 1190 which defines the characteristic inter-hole distance of this arrangement.

[0053] It will appear readily that, while the description of the three embodiments above has been made in progressive order of complexity, the features of the latter embodiments could be adapted on the former ones. For example, through-holes 1180 could be made in the first embodiment, through-holes 1190 could be made in the first and second embodiments, etc.

[0054] In the example described herein, through-holes 1190 are spaced substantially evenly and will have the result of excluding parasite modes within the machining portion which have a frequency which is less than

$f_p = \frac{c}{2s_p \sqrt{\epsilon_r}}$ where s_p is the maximum inter-through-hole spacing for the through-holes 1190.

[0055] Figure 15 shows an exemplary machining process for the superconducting microwave device of Figures 3 to 14.

[0056] In a first operation 1500, the dimensions s and d are calculated for the superconducting microwave device to be manufactured in view of the frequency of the electromagnetic field which is intended to be confined within the resonator portion.

[0057] Thereafter, in an operation 1510 the through-holes 340, 740 or 1140 defining the contour 345, 745 or 1145 are machined in the substrate 310, 710 or 1110, thereby defining the machining portion and the resonator portion.

[0058] Operation 1510 is followed by optional operations 1520, 1530 and 1540 in which respectively the blind hole 370, 770 or 1170, the contour 365, 765 or 1165 and the extra through-holes 780 or 1180 and 1190.

[0059] Once the substrate has been fully machined, it is coated with the superconducting metal in an operation 1550. The Applicant has determined that the following metals can be used: Aluminum (Al), Tantalum (Ta), Niobium (Nb), and more generally all conventional superconducting metals.

[0060] The coating process may be performed as follows: the substrate is first attached by a corner to a rotating plate in a chamber and the vacuum is made in the chamber. During the coating, the device holding the substrate is oriented with different angles in the flow of vaporized metal. Each face (top and bottom) is exposed through different tilt angles (for example 6 different angles or more) in order to coat as homogeneously as possible a first half of the substrate. After the first half of the substrate has been coated, the device is rotated by 180° without breaking the vacuum of the chamber in order to expose the other half to the vaporized metal flow. The other half is then exposed through different tilt angles (for example 6 different angles or more). The coating process results in a coating thickness of several hundreds of nanometers of metal (typically around 300 nm). Of course another coating process can be used and other thicknesses achieved.

[0061] Finally, in an operation 1560, an engraving mask is superposed on the coated substrate, and an

etching process is conducted in order to provide the substrate with the circuit design intended for the superconducting microwave device.

[0062] Figure 16 shows a picture of the superconducting microwave device of the invention after operation 1550. This picture shows how the machining portion is held for the metal coating process.

[0063] Figure 17 shows a zoomed picture of the superconducting microwave device after operation 1560. On this picture, the fully packaged chip is shown, with the transmission line engraved and connectors for ensuring the same potential across the machining portion.

[0064] The invention thus offers a novel superconducting microwave device for hosting qubits. By choosing

ratios $\frac{s}{d}$, the ratio $\frac{\lambda}{4} > s$ will provide that modes

having a frequency of less than $f_m = \frac{c}{4s \sqrt{\epsilon_r}}$ will be properly hosted in the superconducting microwave device.

[0065] It will be appreciated that, while the embodiments show through-holes which are well aligned along circle-shape contours, in alternative embodiments, through-holes could be spaced along a contour having an arbitrary shape, with the limitation that all inter-through-holes spacing and through-hole diameters have to respect the invention's s - and λ ratios. For example, the through-holes could be on two respective circle-shaped contours (one being bigger than the other), and be arranged alternately on the smaller and the bigger contour, or even more randomly and/or more randomly shaped contours. Within the present disclosure, the through-holes are described as evenly spaced. It will be understood that this spacing may not necessarily be exactly

equal as long as the $\frac{s}{d}$ ratio is fulfilled.

[0066] It will be appreciated that, while the above examples show a superconducting microwave device comprising a machining portion and a resonator portion, several resonator portions may be comprised on said substrate such that it comprises several resonator portions for a given machining single portion. To that end, it is sufficient to provide several plurality of through-holes forming respective first contours. An example is schematically shown on Figure 18 on which the substrate is referenced 1810, the machining portion is referenced 1820, the resonators are referenced 1830, 1831 and 1832, and the first contours defining them are referenced 1845, 1846 and 1847.

Claims

1. Superconducting microwave device for hosting qubits comprising a substantially planar substrate (310, 710, 1110) coated with a superconducting metal,

wherein said substantially planar substrate (310, 710, 1110) comprises a plurality of through-holes (340, 740, 1140), said plurality of through-holes being arranged to define a first contour (345, 745, 1145) which divides said substantially planar substrate (310, 710, 1110) into a resonator portion (330, 730, 1130) enclosed within said first contour (345, 745, 1145) and a machining portion (320, 720, 1120) comprising a holding area for maintaining said superconducting qubit device (300, 700, 1100) during the substantially planar substrate superconducting metal coating, said through-holes (340, 740, 1140) being arranged about said first contour (345,

745, 1145) such that $4 > \frac{s}{d} > 1$ where s is the inter-through-hole spacing and d is the through-hole diameter.

2. Superconducting microwave device according to claim 1, in which the resonator portion (330, 730, 1130) has a resonance frequency which is less than

$f_m = \frac{c}{4s\sqrt{\epsilon_r}}$, where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate (310, 710, 1110).

3. Superconducting microwave device according to one of the preceding claims, in which the resonator portion (330, 730, 1130) comprises a blind hole (370, 770, 1170, 1370).

4. Superconducting microwave device according to one of the preceding claims, in which the resonator portion (330, 730, 1130) comprises a second plurality of through-holes (760, 1160) defining a second contour (365, 765, 1165), wherein the through-holes (760, 1160) defining said second contour (365, 765, 1165) have dimensions of diameter and inter-through-hole spacing substantially identical to those of said first contour (345, 745, 1165).

5. Superconducting microwave device according to one of the preceding claims, in which the machining portion (320, 720, 1120) further comprises a third plurality of through-holes (1190) arranged such that

$\frac{s_p}{d_p} > 1$ where s_p is the maximum inter-through-hole spacing for the third plurality of through-holes (1190) and d_p is the third plurality of through-holes (1190) diameter, whereby only parasite electromagnetic modes having a frequency of more than

$f_p = \frac{c}{2s_p\sqrt{\epsilon_r}}$ will be allowed in the machining portion (320, 720, 1120), where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the

substantially planar substrate (310, 710, 1110).

6. Superconducting microwave device according to one of the preceding claims, in which said plurality of through-holes are arranged to define a plurality of first contours (1845, 1846, 1847) which divide said substantially planar substrate (1810) into respective resonator portions (1830, 1831, 1832) each enclosed within a respective one of said first contours (1845, 1846, 1847) and said machining portion (1820).

7. Method of fabricating a superconducting microwave device for hosting qubits comprising the following operations:

a) providing a substantially planar substrate (310, 710, 1110),

b) providing a plurality of through-holes in said substantially planar substrate (310, 710, 1110), said plurality of through-holes (340, 740, 1140) being arranged to define a first contour (345, 745, 1145) which divides said substantially planar substrate (310, 710, 1110) into a resonator portion (330, 730, 1130) enclosed within said first contour (345, 745, 1145) and a machining portion (320, 720, 1120), said through-holes (340, 740, 1140) being arranged about said first contour (345, 745, 1145) such that

$4 > \frac{s}{d} > 1$ where s is the inter-through-hole spacing and d is the through-hole diameter, and c) coating the substantially planar substrate (310, 710, 1110) of operation b).

8. Method according to claim 7, further comprising the following operation:

d) engraving circuit design elements by providing a circuit mask on the substantially planar substrate (310, 710, 1110) of operation c) and etching.

9. Method according to claim 7 or 8, in which operation b) provides a resonator portion (330, 730, 1130) having a resonance frequency which is less than

$f_m = \frac{c}{4s\sqrt{\epsilon_r}}$, where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate (310, 710, 1110).

10. Method according to one of claims 7 to 9, in which operation b) further comprises providing a blind hole (370, 1170, 1370) in said resonator portion (330, 730, 1130).

11. Method according to one of claims 7 to 10, in which operation b) further comprises providing the resonator portion (330, 730, 1130) with a second plurality of

through-holes (760, 1160) defining a second contour (765, 1165), wherein the through-holes (760, 1160) defining said second contour (765, 1165) have dimensions of diameter and inter-through-hole spacing substantially identical to those of said first contour (345, 745, 1145). 5

12. Method according to one of one of claims 7 to 11, in which operation b) further comprises providing the machining portion (320, 720, 1120) with a third plurality of through-holes (1190) arranged such that 10

$\frac{s_p}{d_p} > 1$ where s_p is the maximum inter-through-hole spacing for the third plurality of through-holes (1190) and d_p is the third plurality of through-holes (1190) diameter, whereby only parasite electromagnetic modes having a frequency of more than 15

$f_p = \frac{c}{2s_p \sqrt{\epsilon_r}}$ will be allowed in the machining portion (320, 720, 1120), where c is the speed of light in vacuum and ϵ_r is the dielectric permittivity of the substantially planar substrate (310, 710, 1110). 20

13. Method according to one of claims 7 to 12, wherein operation c) comprises: 25

c1) holding the substantially planar substrate (310, 710, 1110) by a corner of said machining portion (320, 720, 1120) in a coating chamber, 30
c2) making vacuum in said coating chamber,
c3) vaporizing metal in said coating chamber while orienting said substantially planar substrate (310, 710, 1110) about a plurality of different angles in the flow of vaporized metal, 35
c4) rotating the substantially planar substrate (310, 710, 1110) by 180° without breaking the vacuum of said coating chamber, and
c5) vaporizing metal in said coating chamber while orienting said rotated substantially planar substrate (310, 710, 1110) about a plurality of different angles in the flow of vaporized metal. 40

14. Method according to one of claims 7 to 13, in which operation b) comprises providing a plurality of through which are arranged to define a plurality of first contours (1845, 1846, 1847) dividing said substantially planar substrate (1810) into respective resonator portions (1830, 1831, 1833) each enclosed within a respective one of said first contours (1845, 1846, 1847) and said machining portion (1820). 45 50

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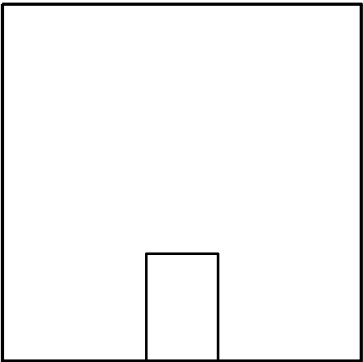


Fig.1

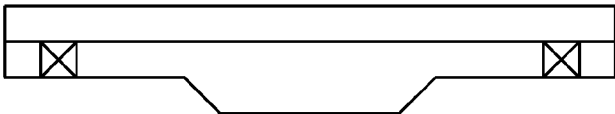


Fig.2

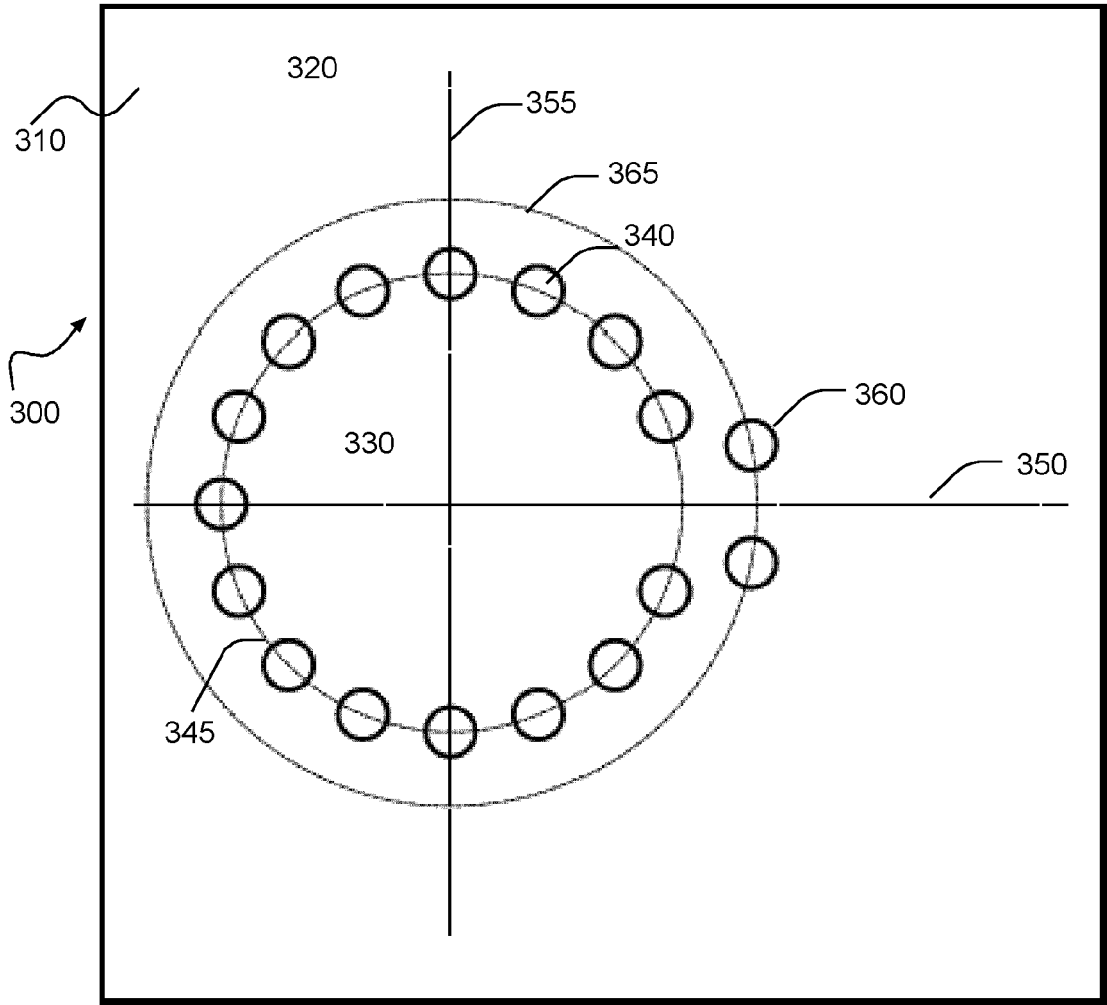


Fig.3

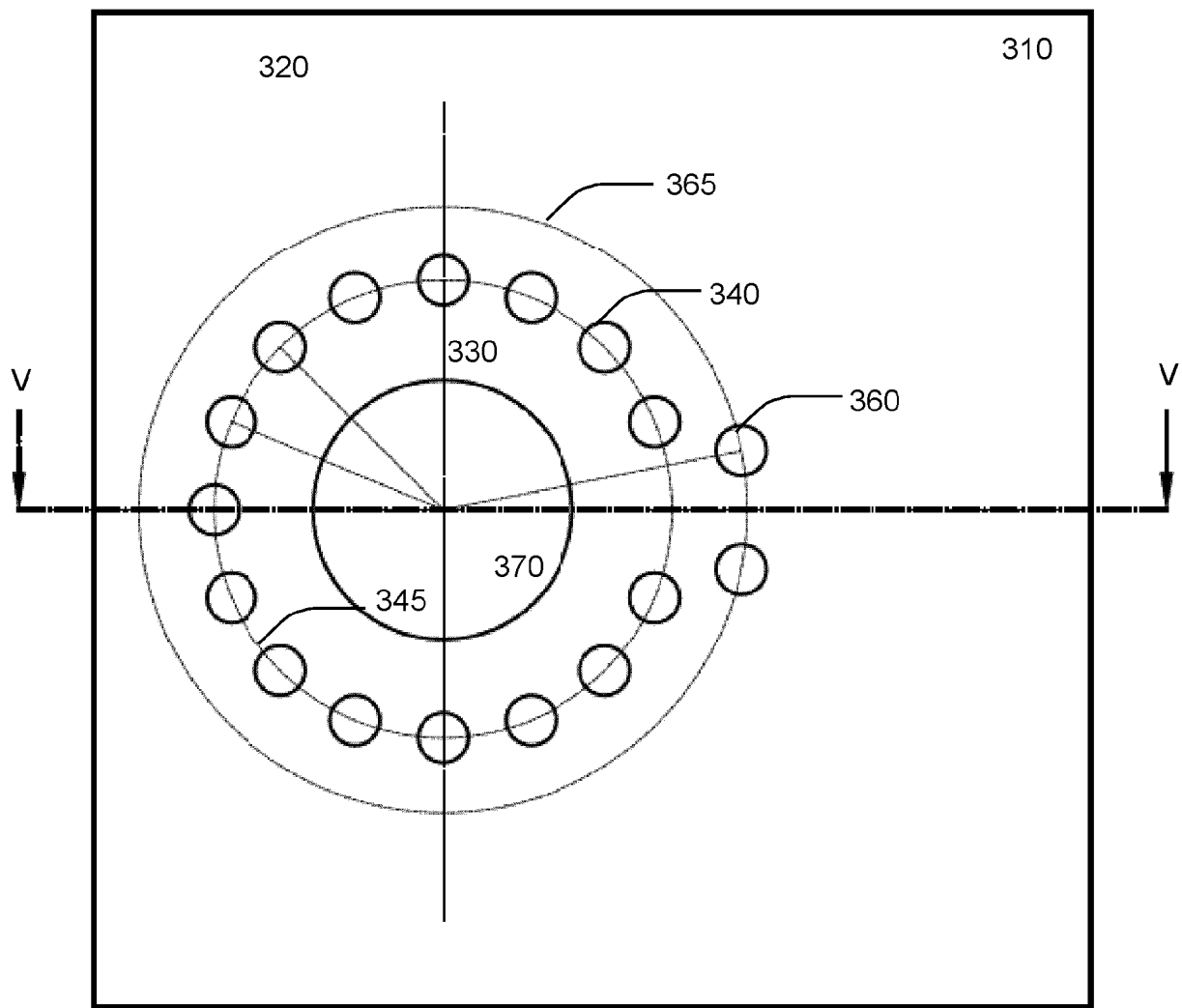


Fig.4

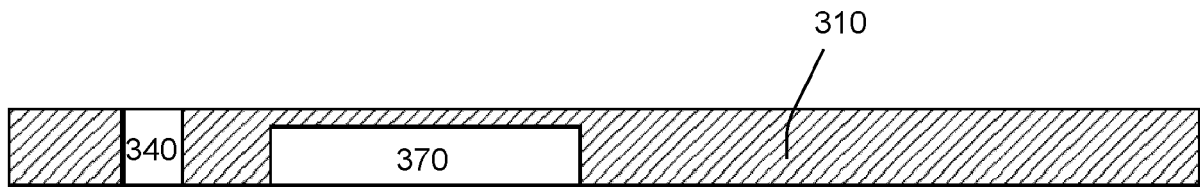


Fig.5

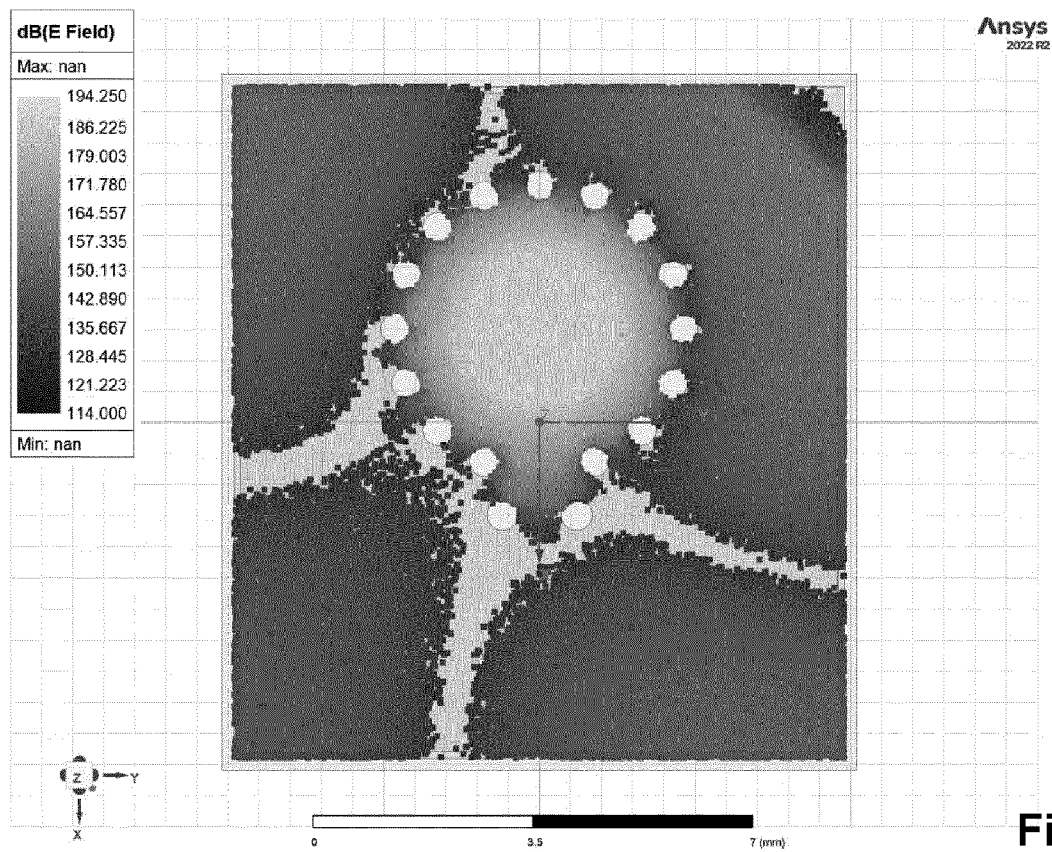


Fig.6

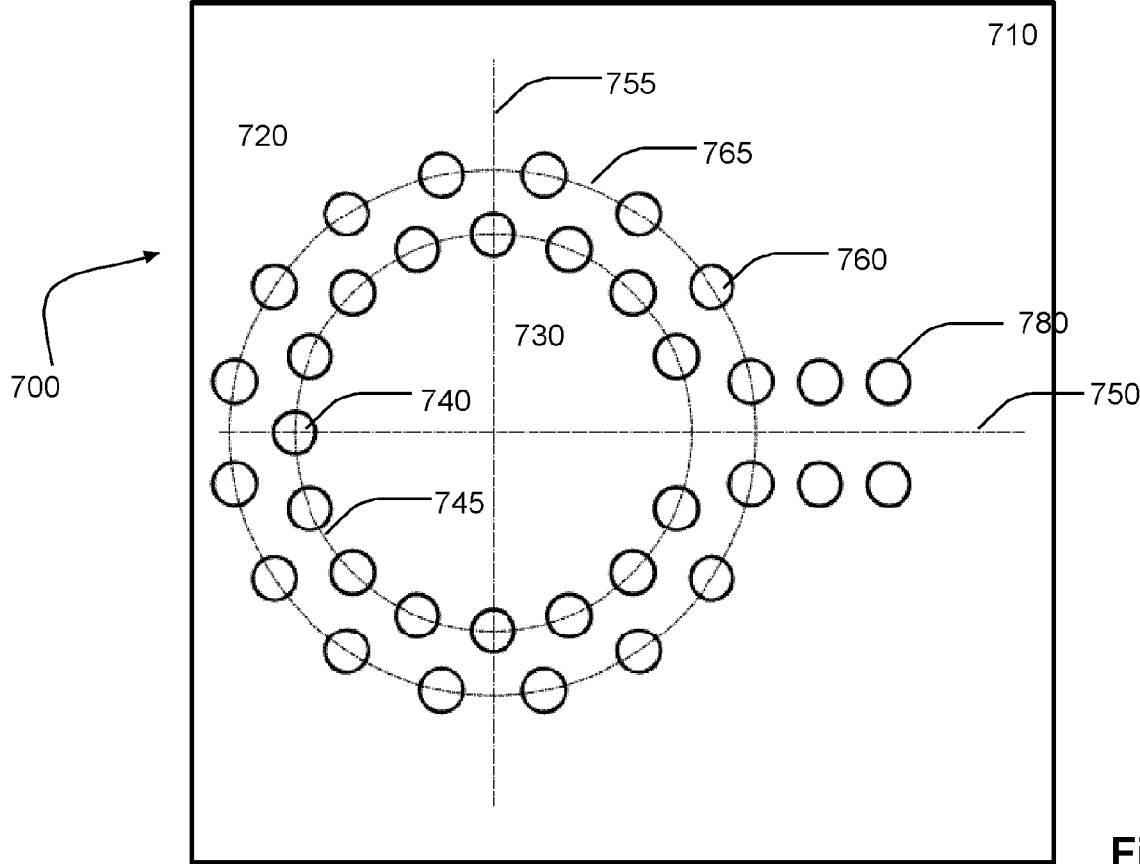


Fig.7

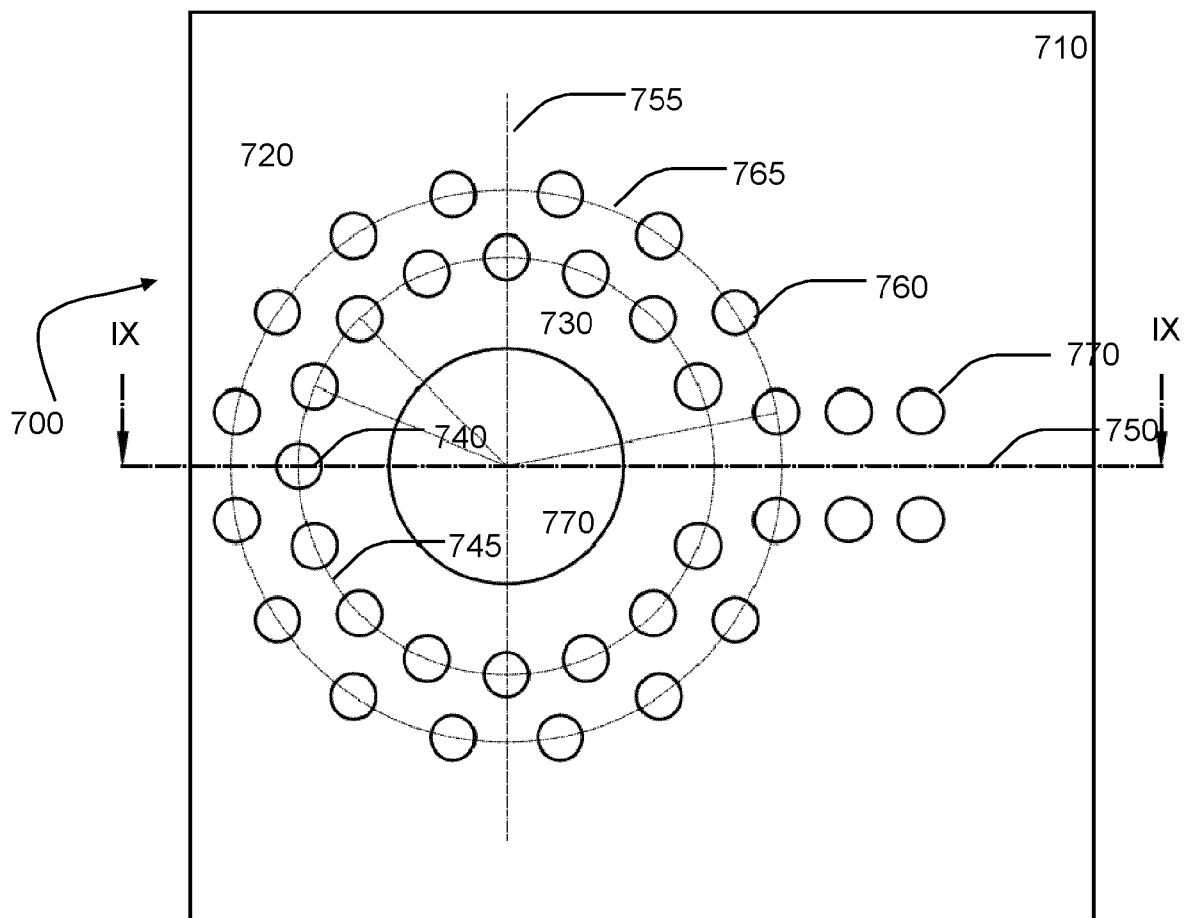


Fig.8

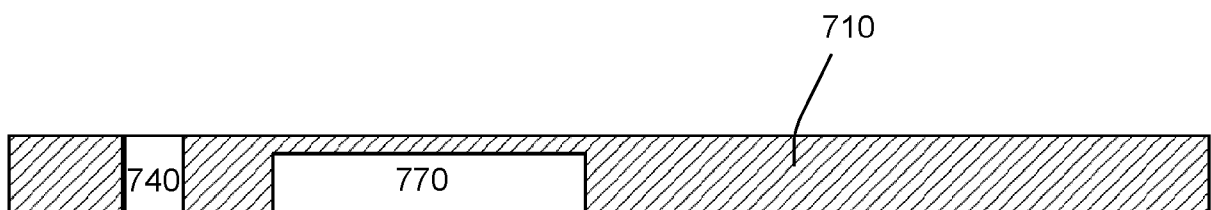


Fig.9

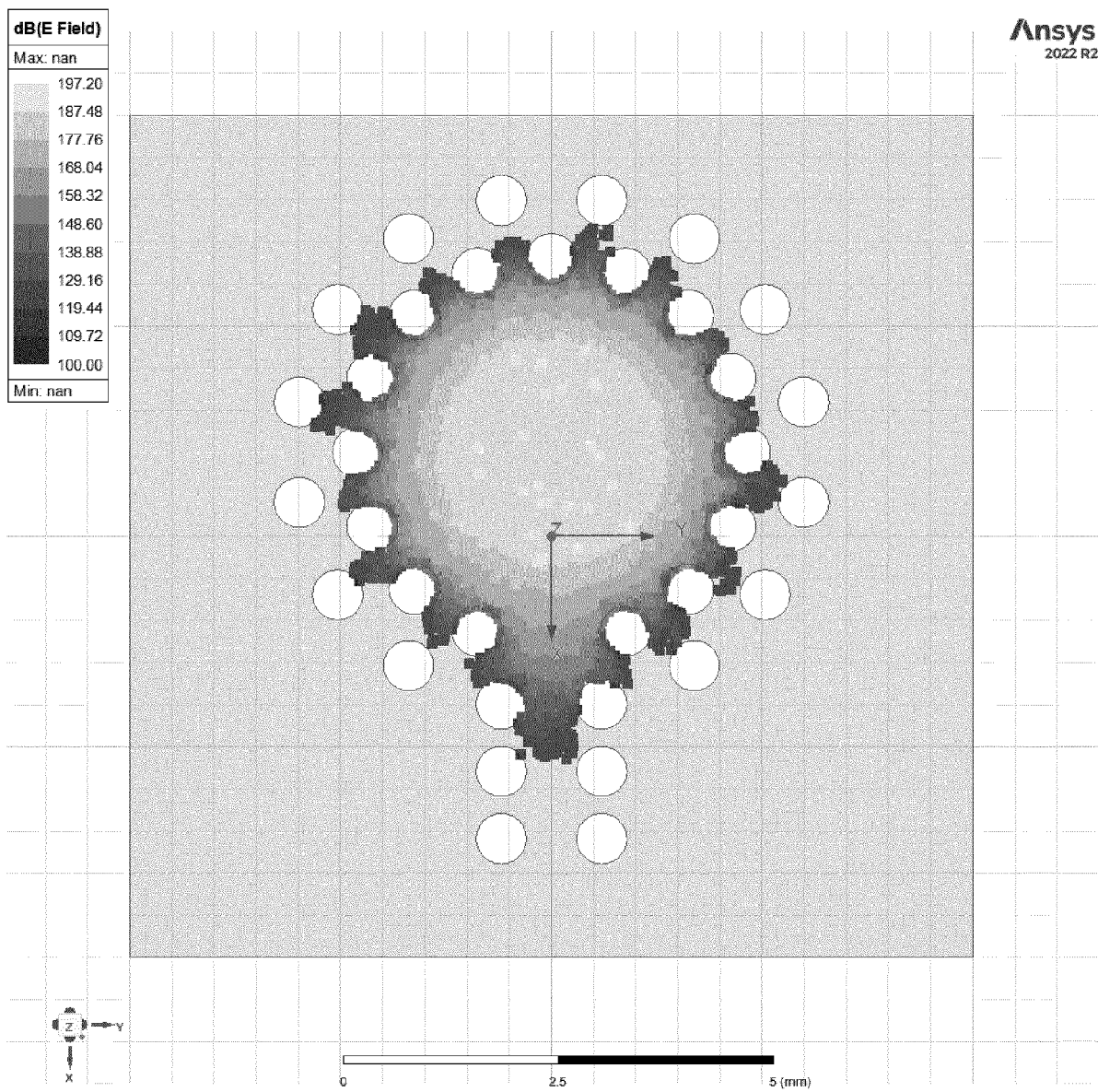


Fig.10

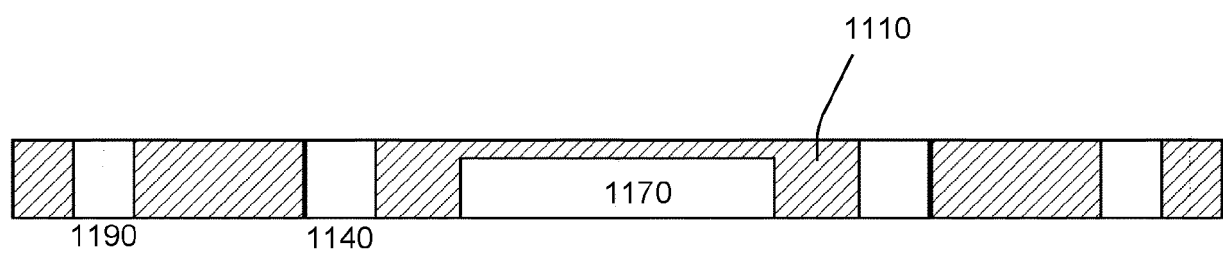


Fig.13

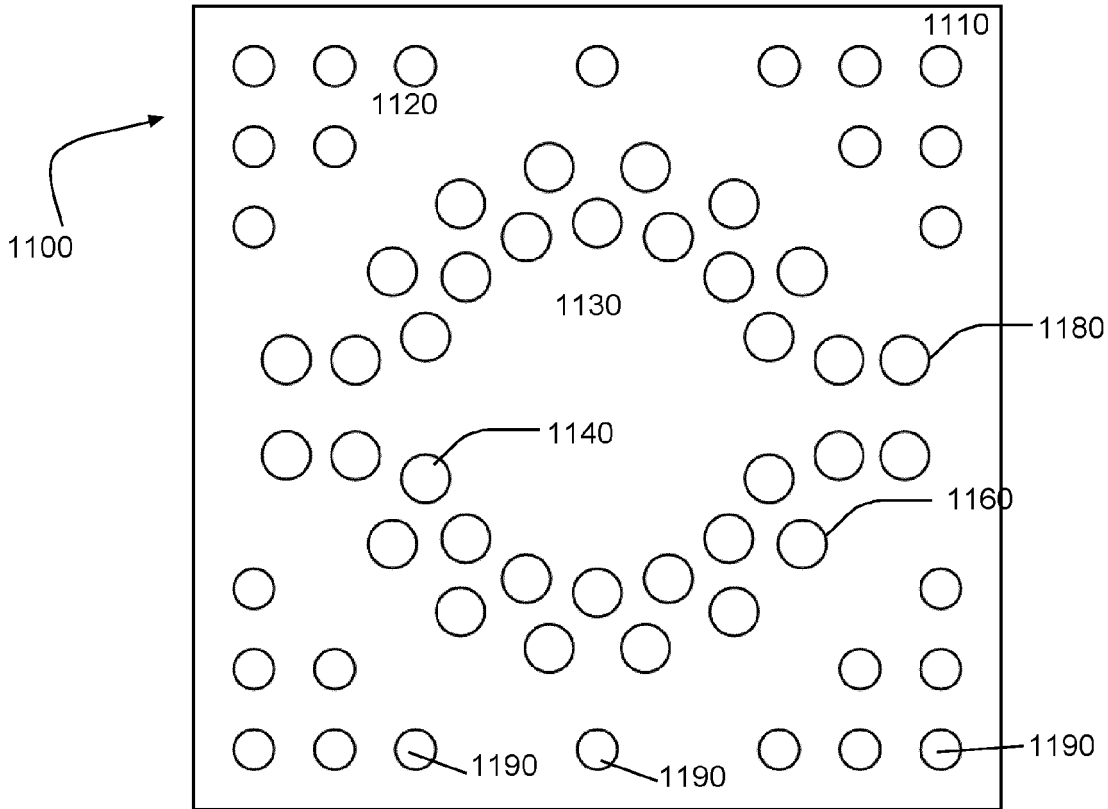


Fig.11

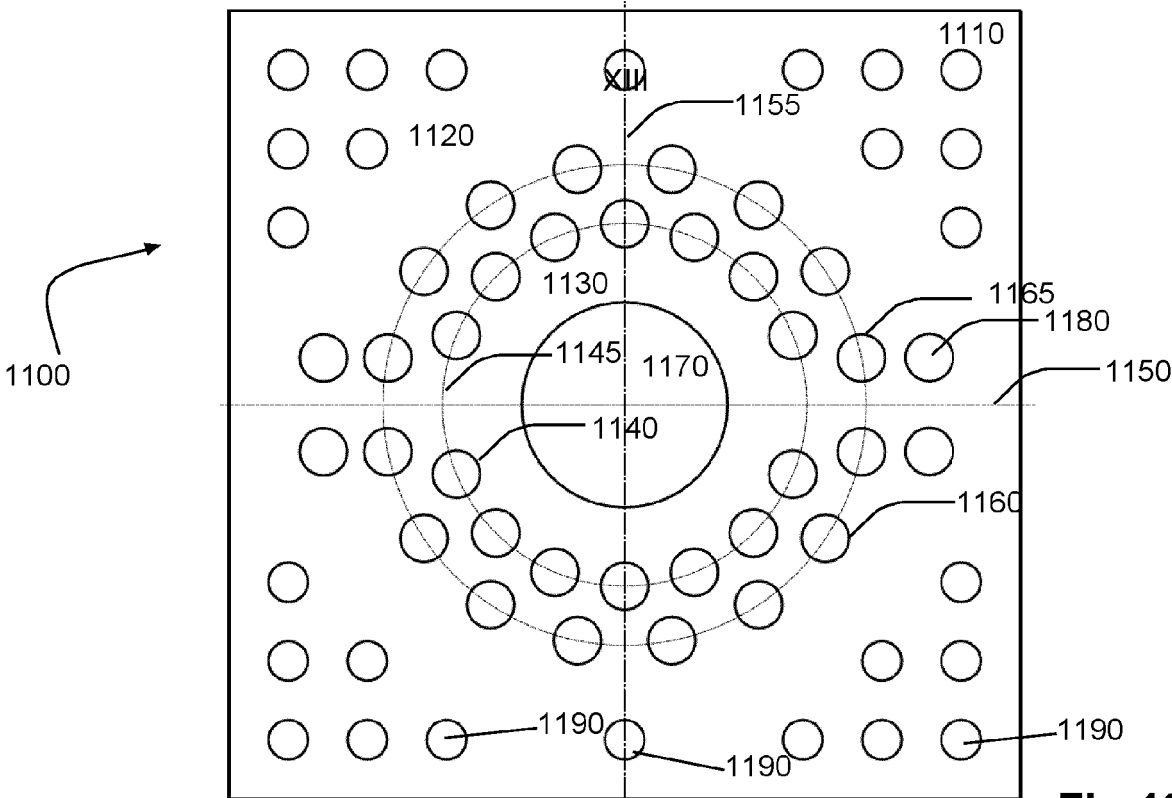


Fig.12

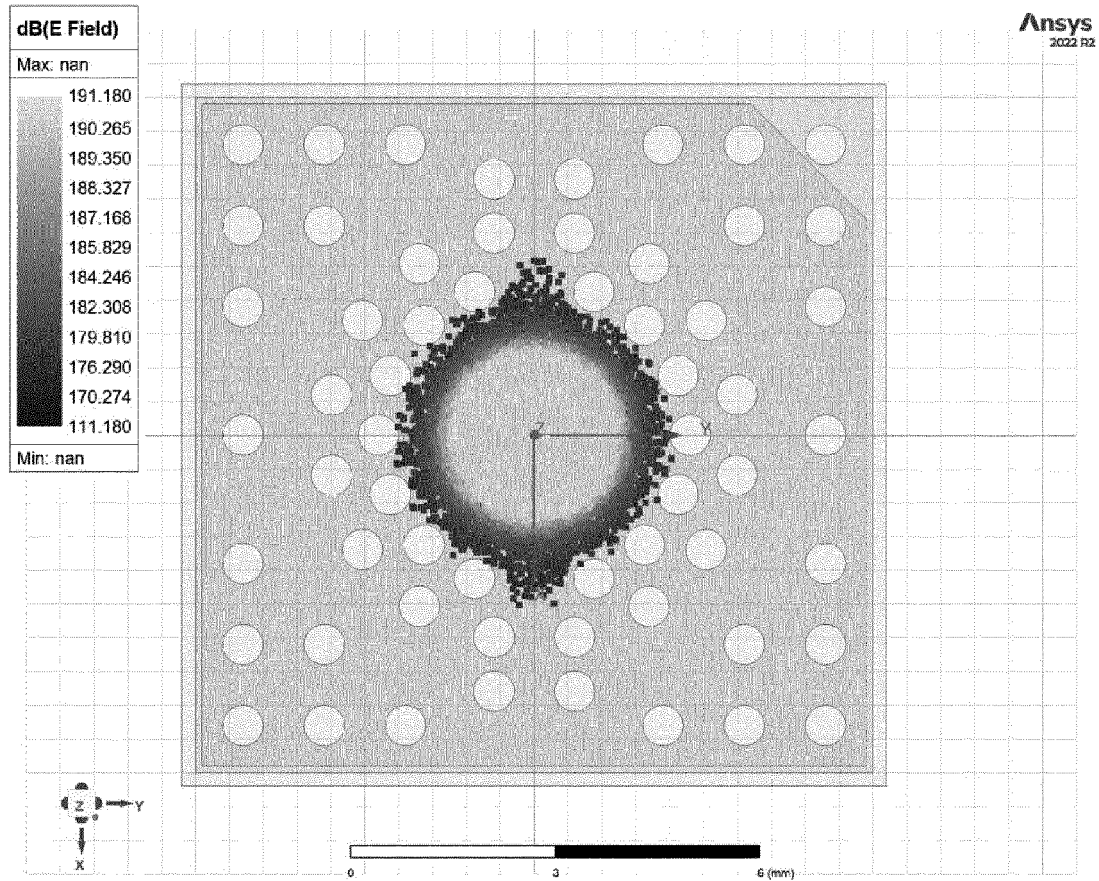


Fig.14

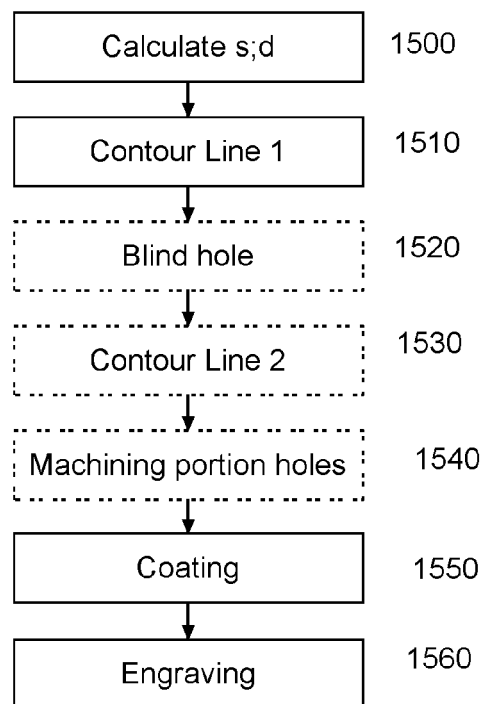


Fig.15

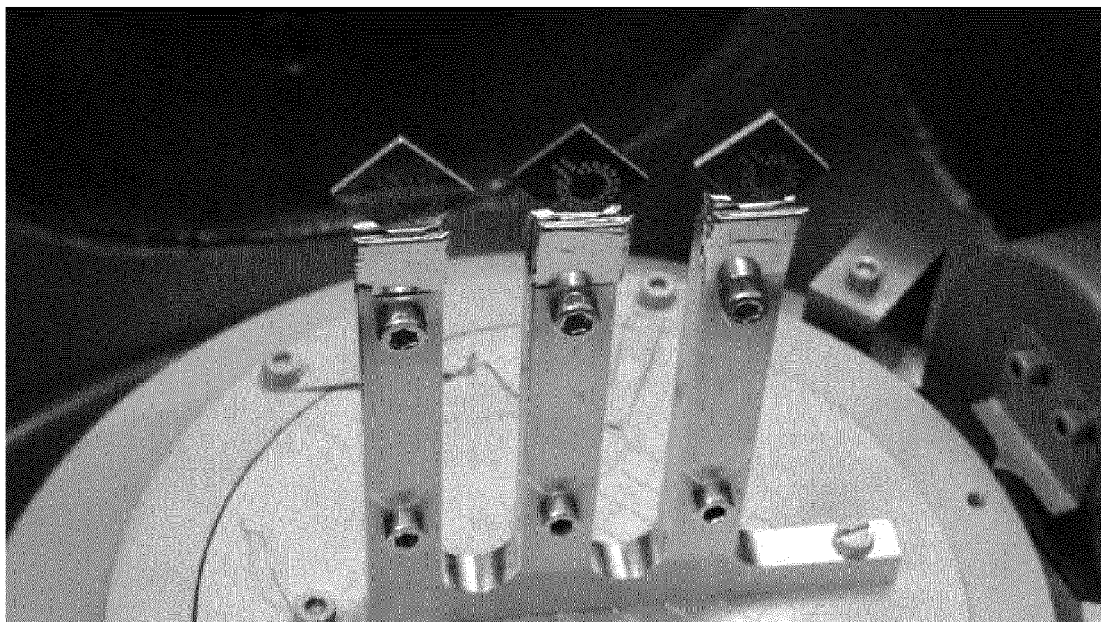


Fig.16

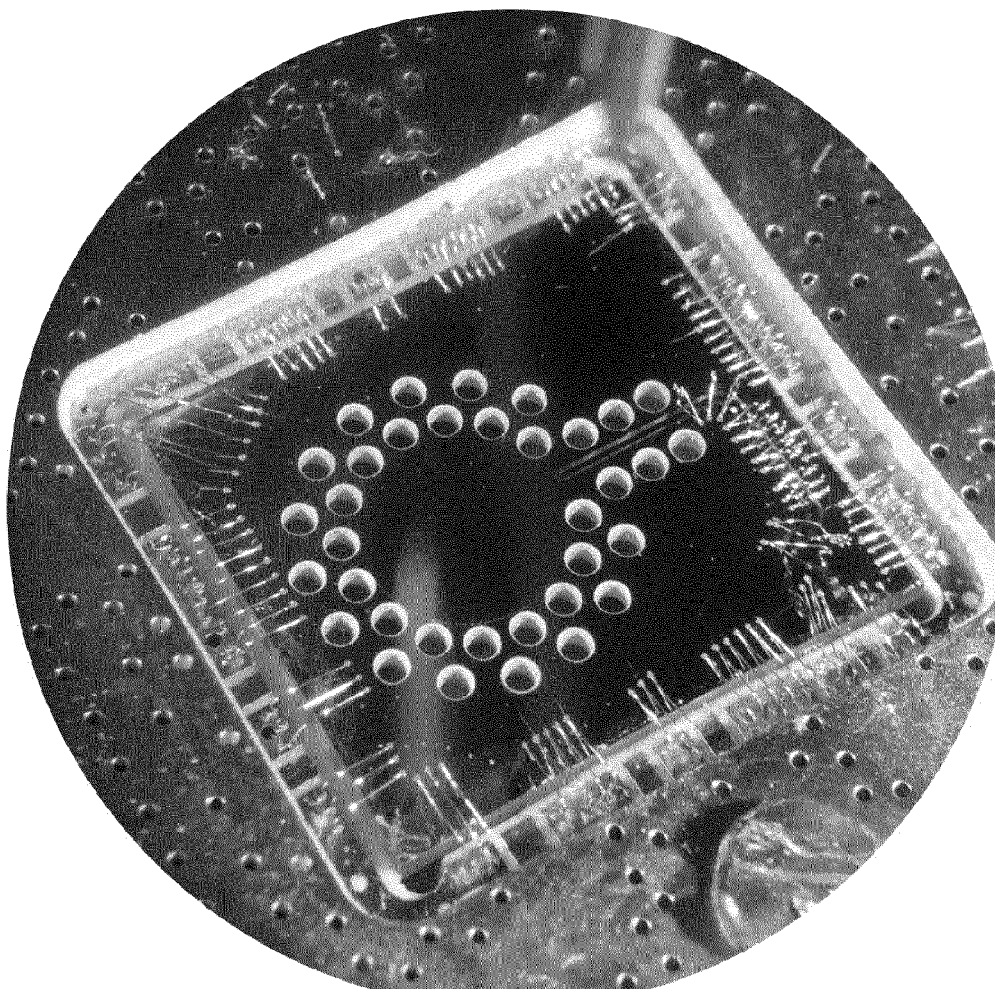


Fig.17

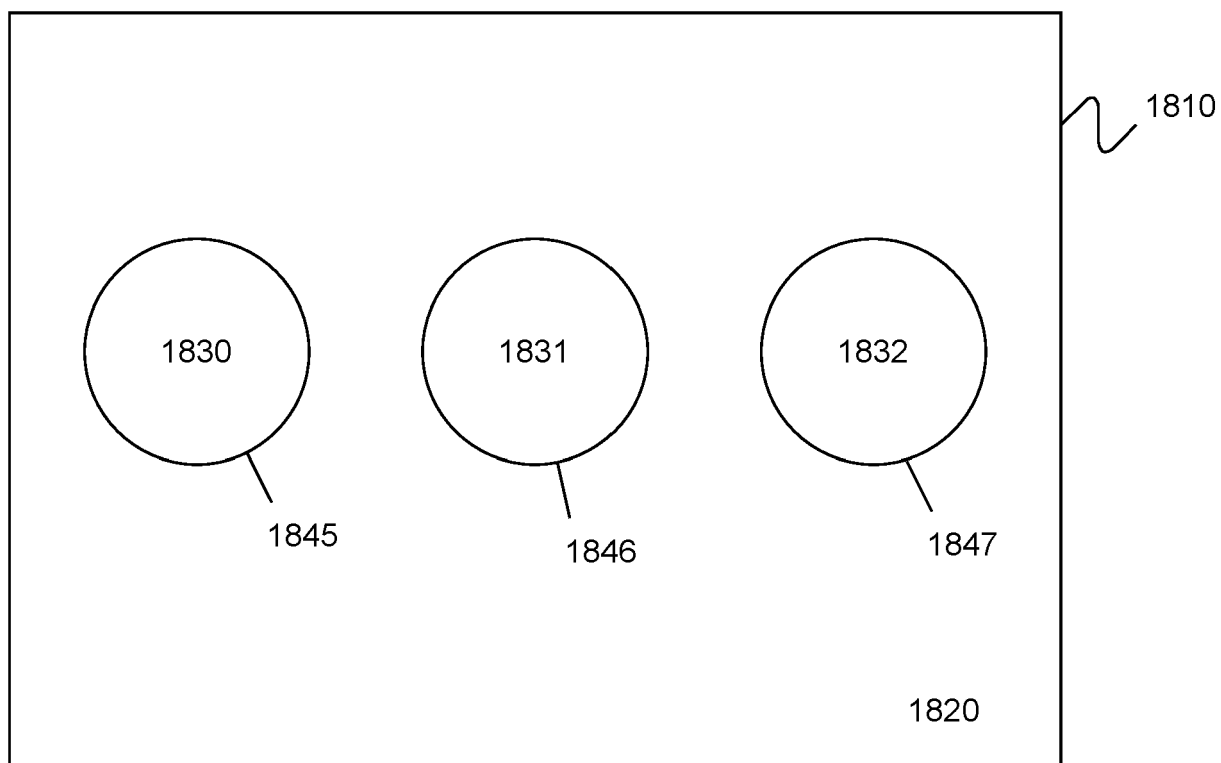


Fig.18



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Place of search		Date of completion of the search	Examiner
The Hague		12 March 2024	Pastor Jiménez, J
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X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document			
T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			



EUROPEAN SEARCH REPORT

Application Number

EP 23 30 6731

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The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
The Hague		12 March 2024	Pastor Jiménez, J
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